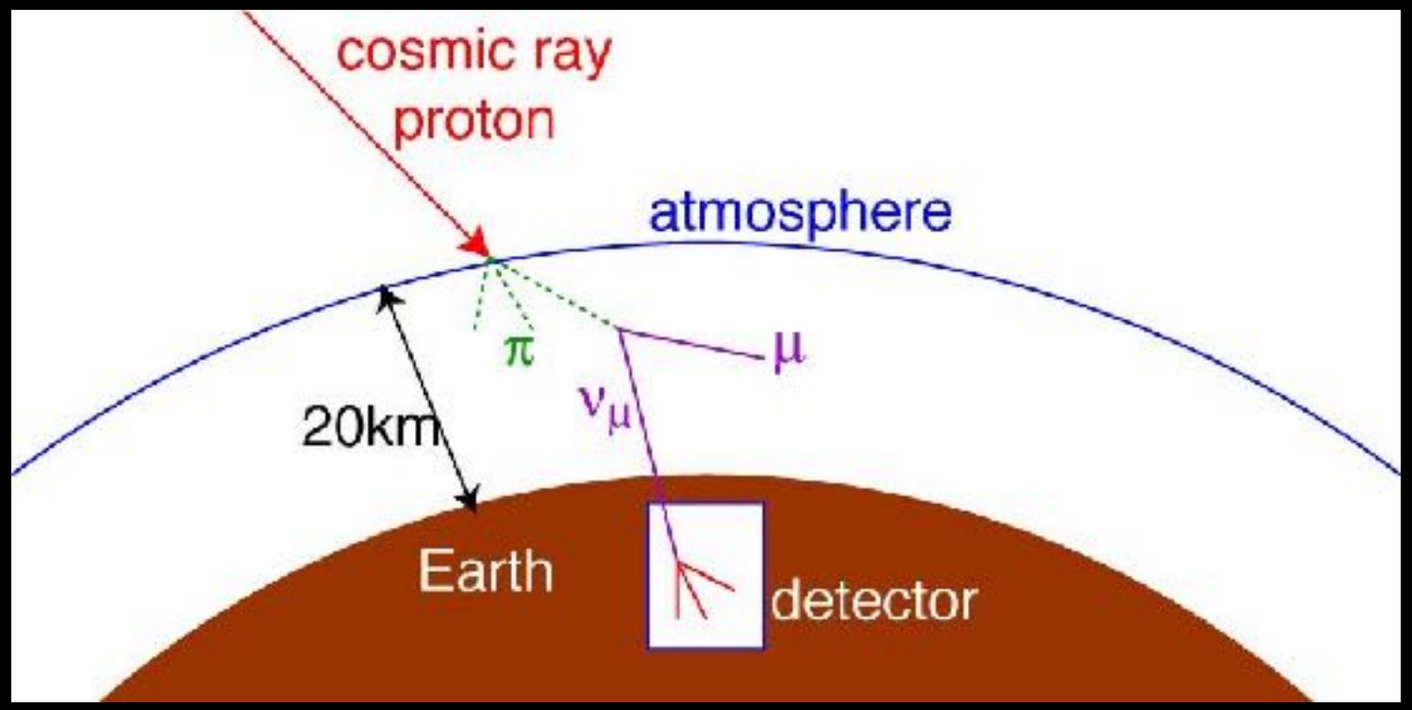
Studying the Cosmos from Underground

Hitoshi Murayama
Kavli IPMU, University of Tokyo
UC Berkeley, Lawrence Berkeley Laboratory
Okayama University, May 23, 2017

Cosmic Rays



Protons come from outer space.
They make muons in the atmosphere.
About a *thousand* of them go through
our body every minute like X-ray.

How did the Universe begin?

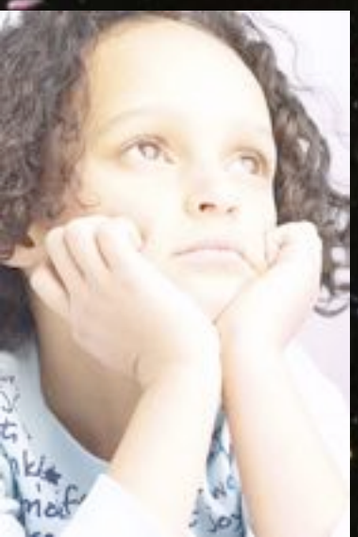
What is its fate?

What is it made of?

What are its fundamental laws?

Where do we come from?

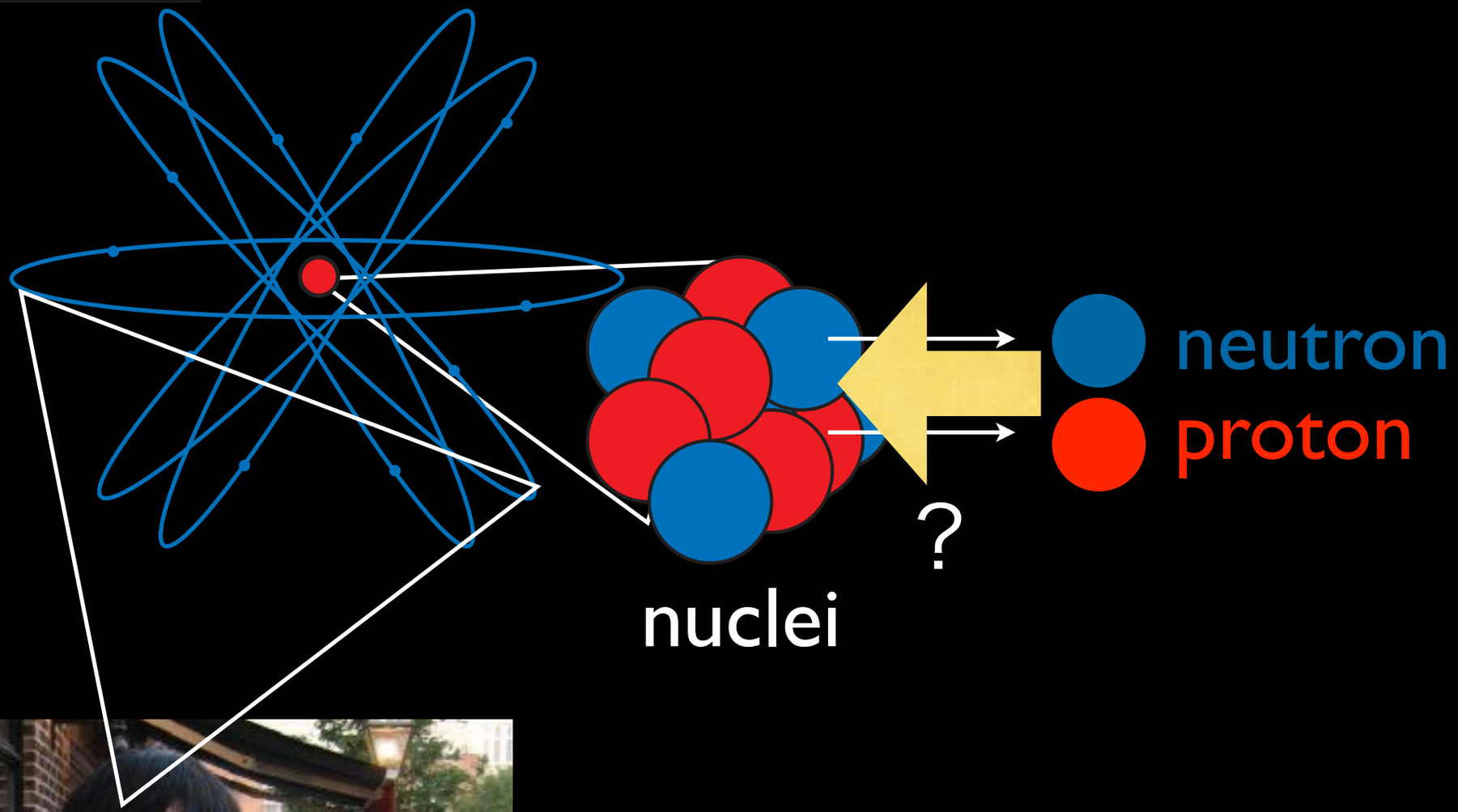
now in the realm of science!



Outline

1. Where the elements come from
2. How the stars were born
3. Where the matter comes from

atoms



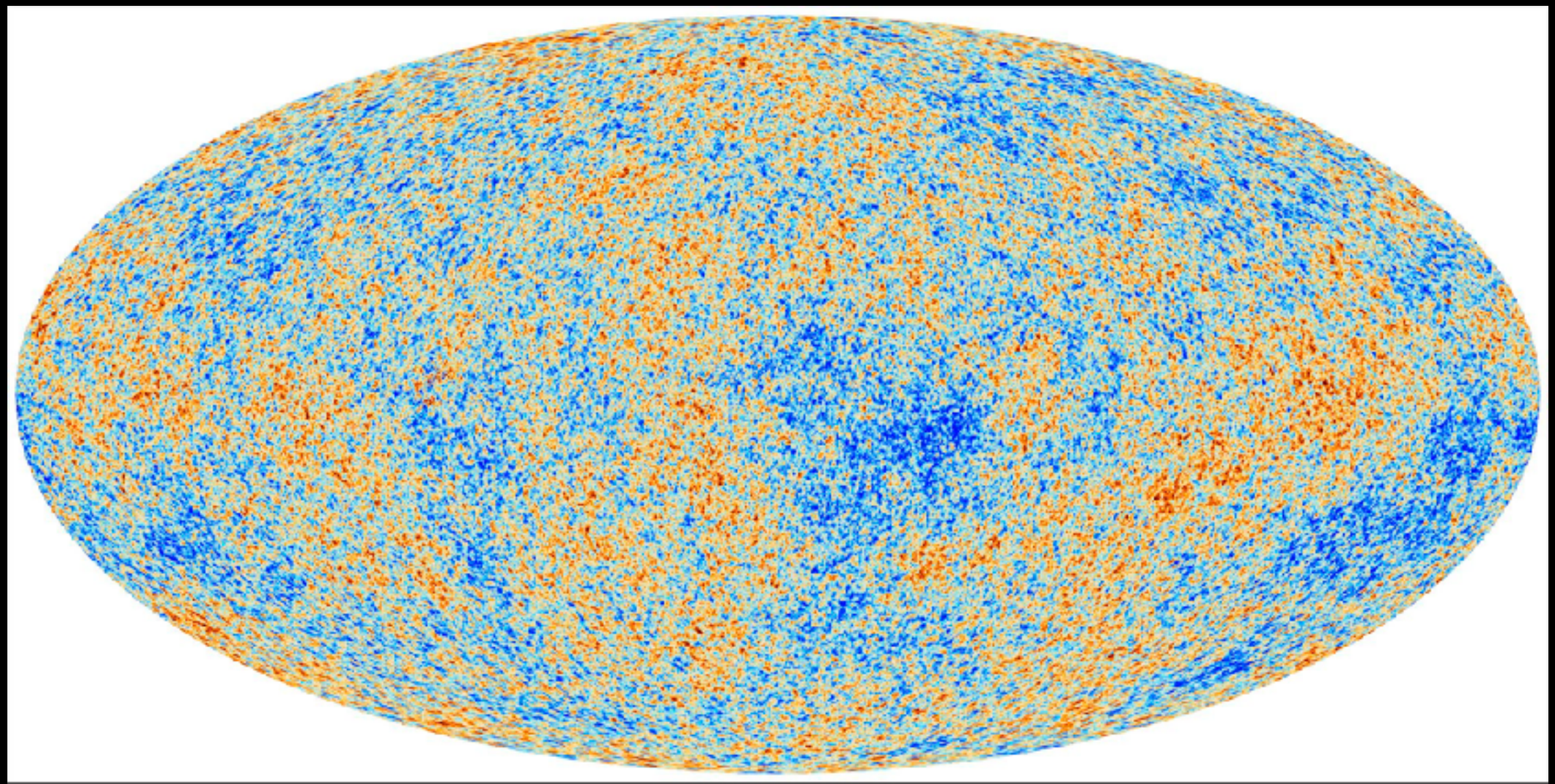
neutron

proton

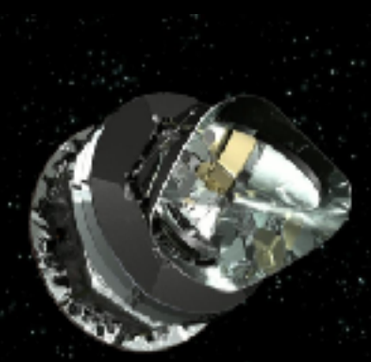
?

nuclei

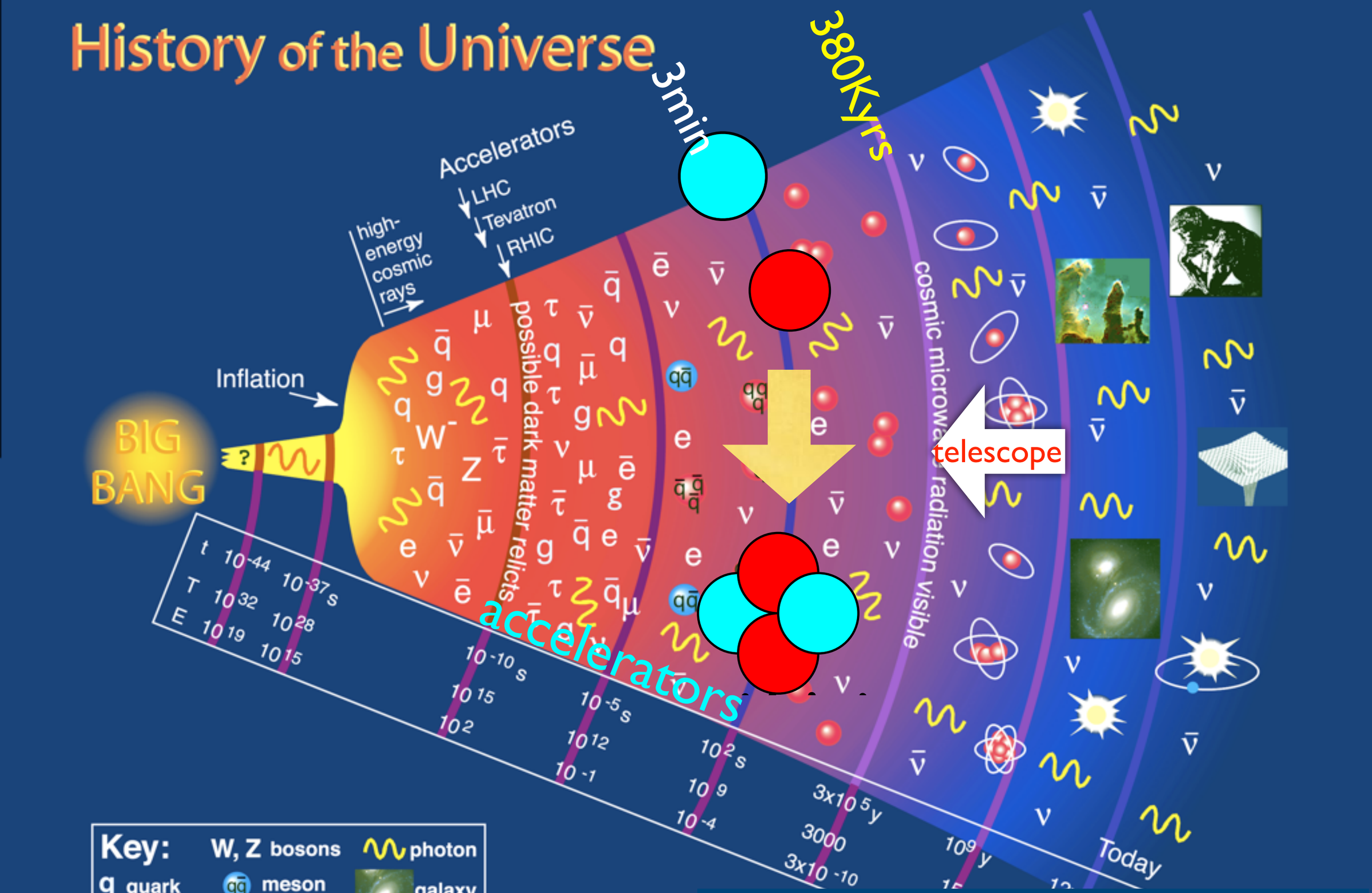
“Wall” @ 13.8 Blyrs



You can never “see” beyond this wall
with a telescope



History of the Universe

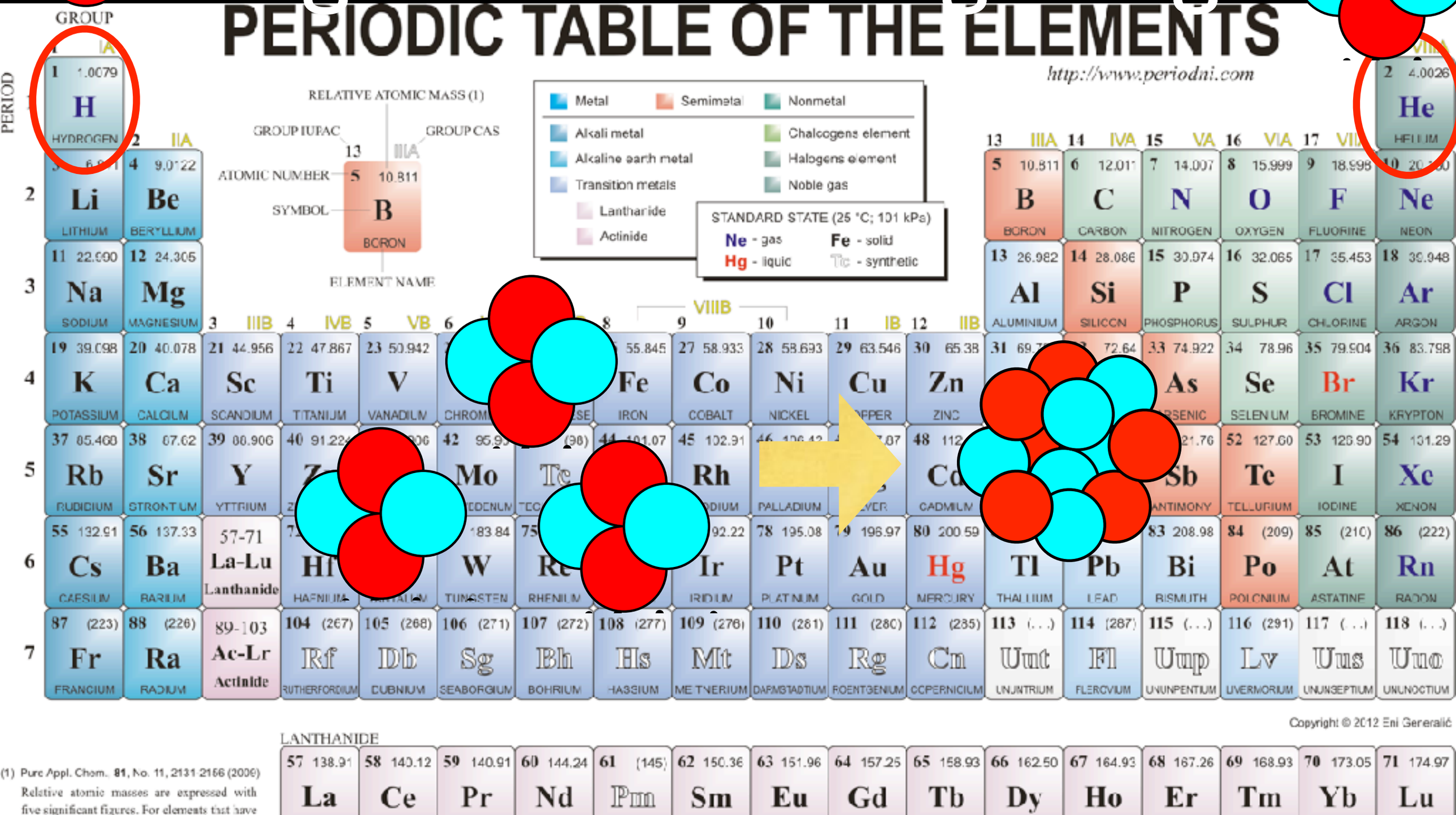


Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
qq meson
baryon
ion
atom
photon
galaxy
star
black hole

Particle Data Group, LB

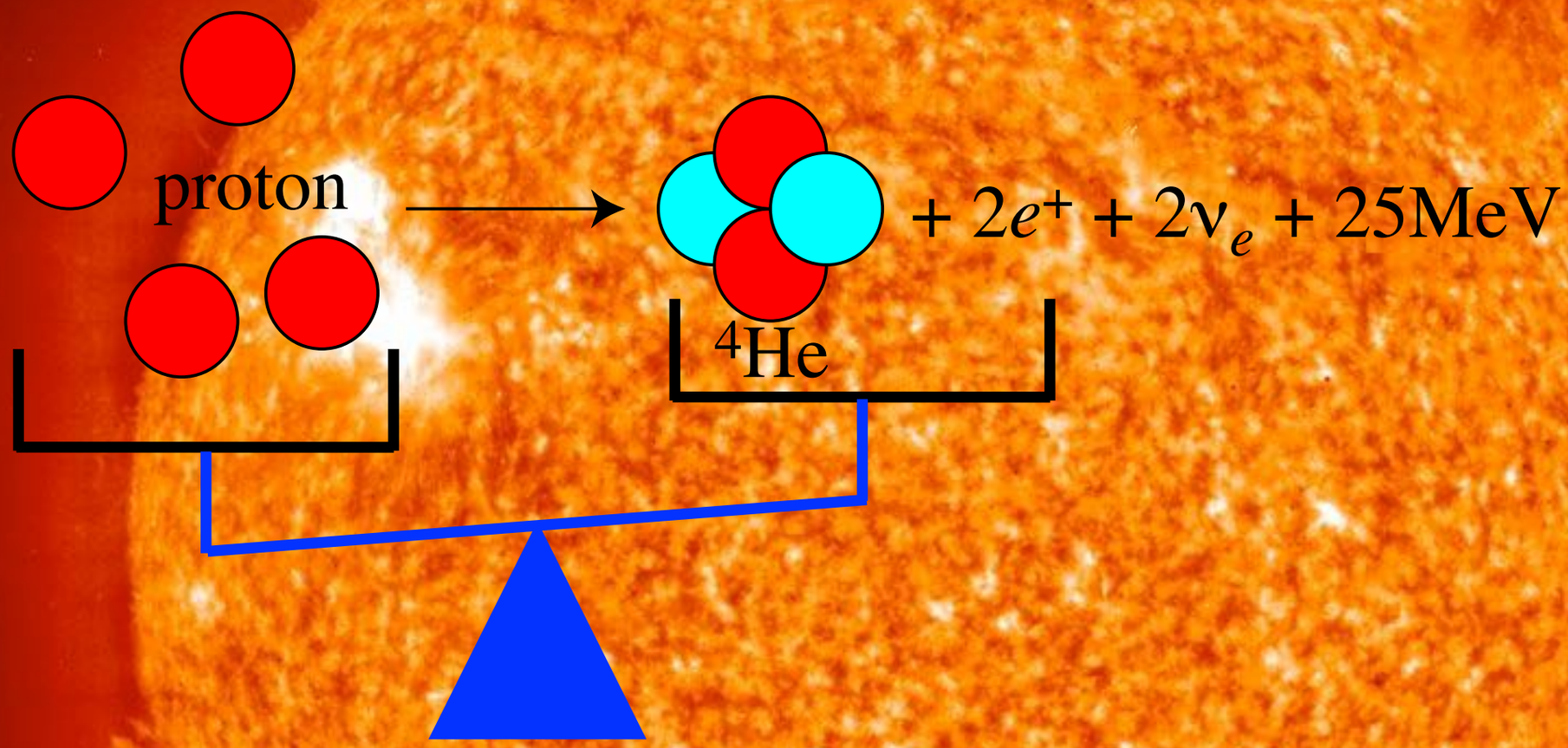
Big Bang made H:He ~ 3:1
agrees with observations

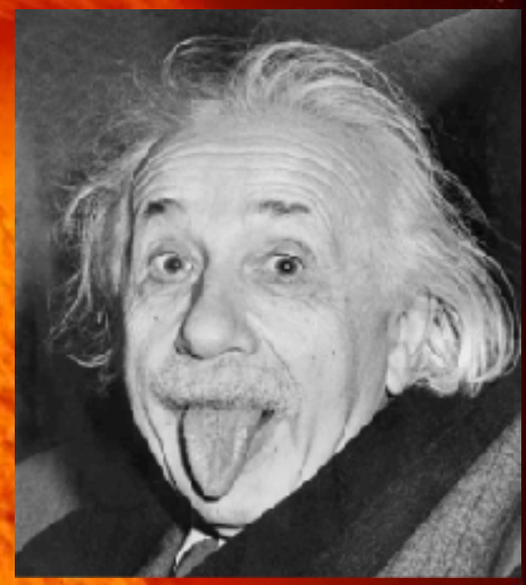
only hydrogen and helium right after the Big Bang



(1) Pure Appl. Chem. **81**, No. 11, 2131–2156 (2009)
Relative atomic masses are expressed with five significant figures. For elements that have no stable nuclides, the value enclosed in

Why does the Sun shine?





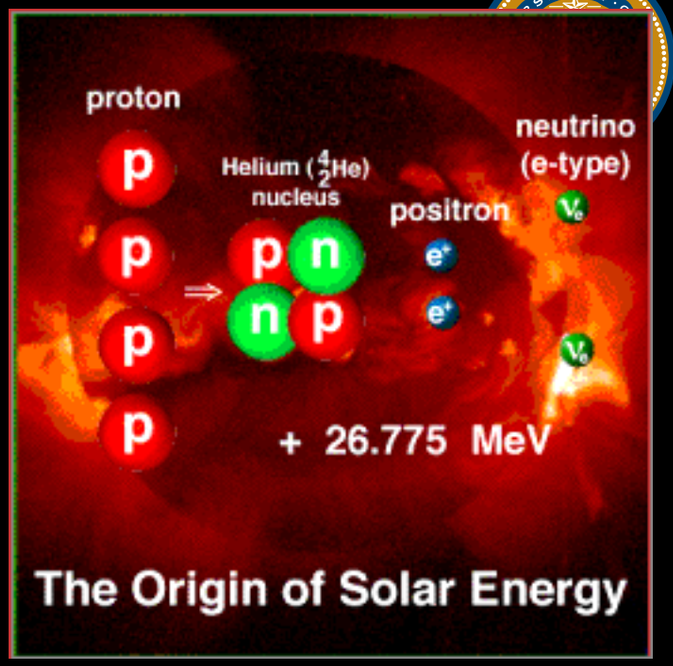
$E=mc^2$

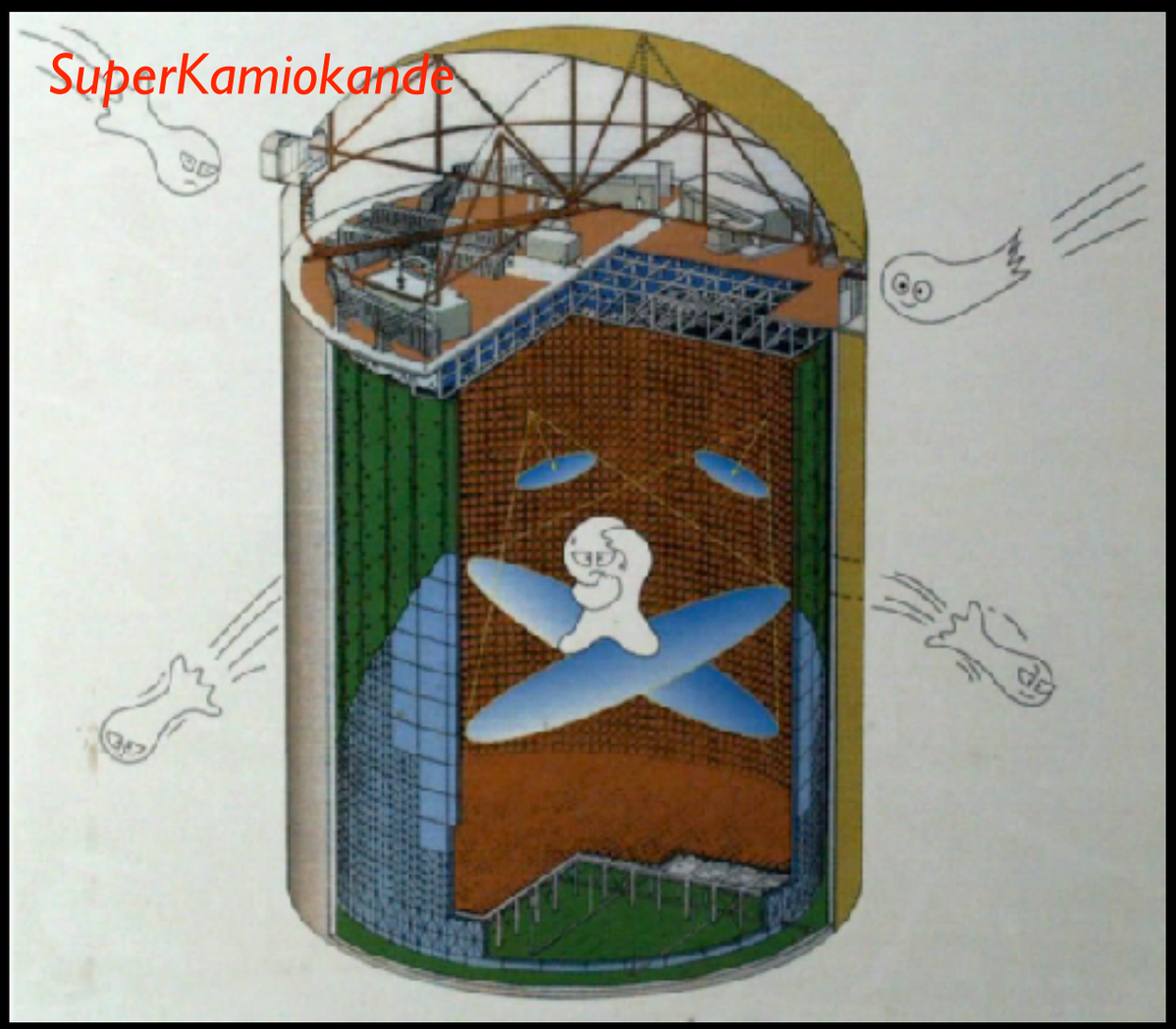
the Sun is getting
lighter by
4 million tons
every second

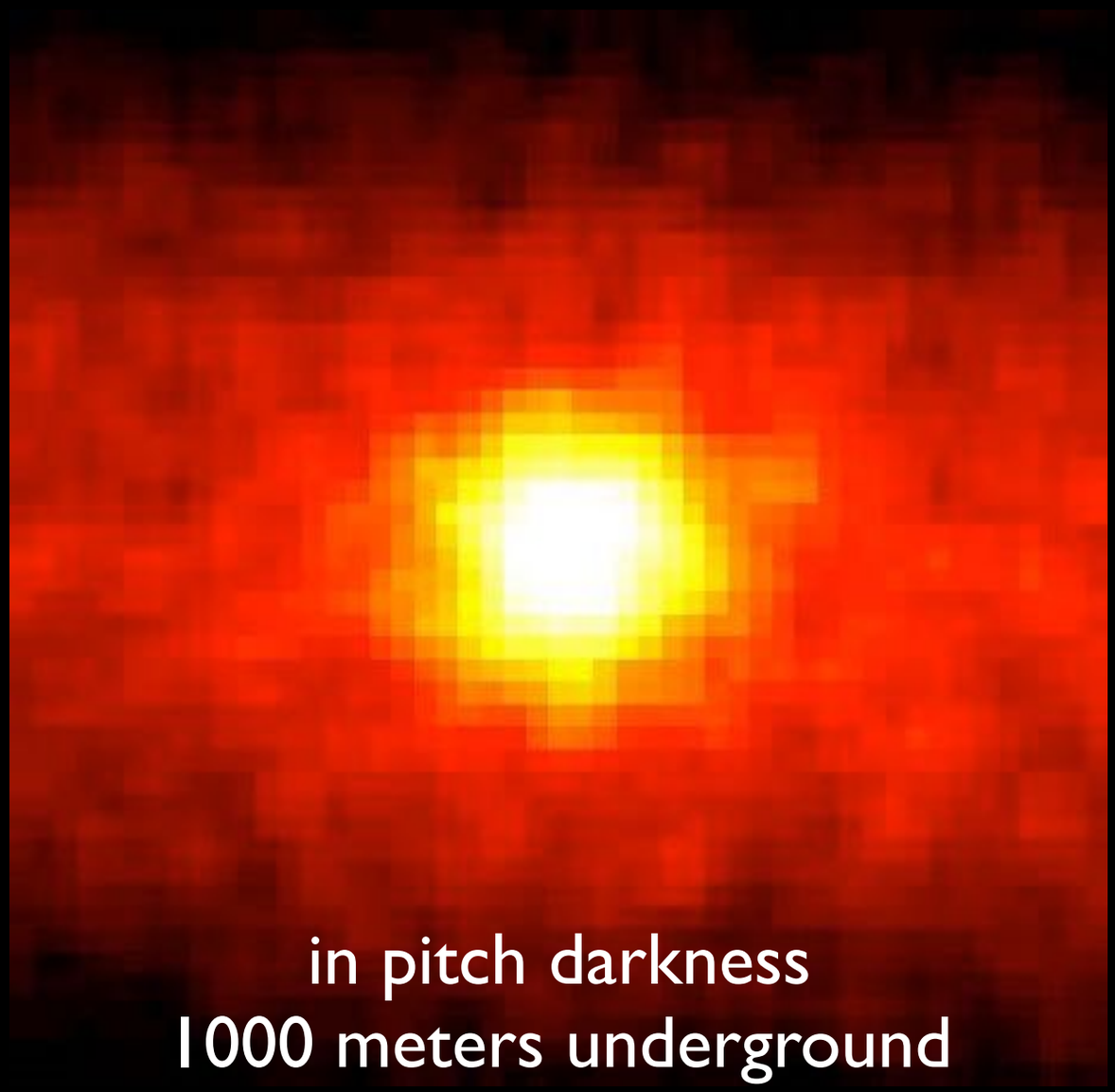
a hundred trillion
neutrinos go through
our body every second

evidence

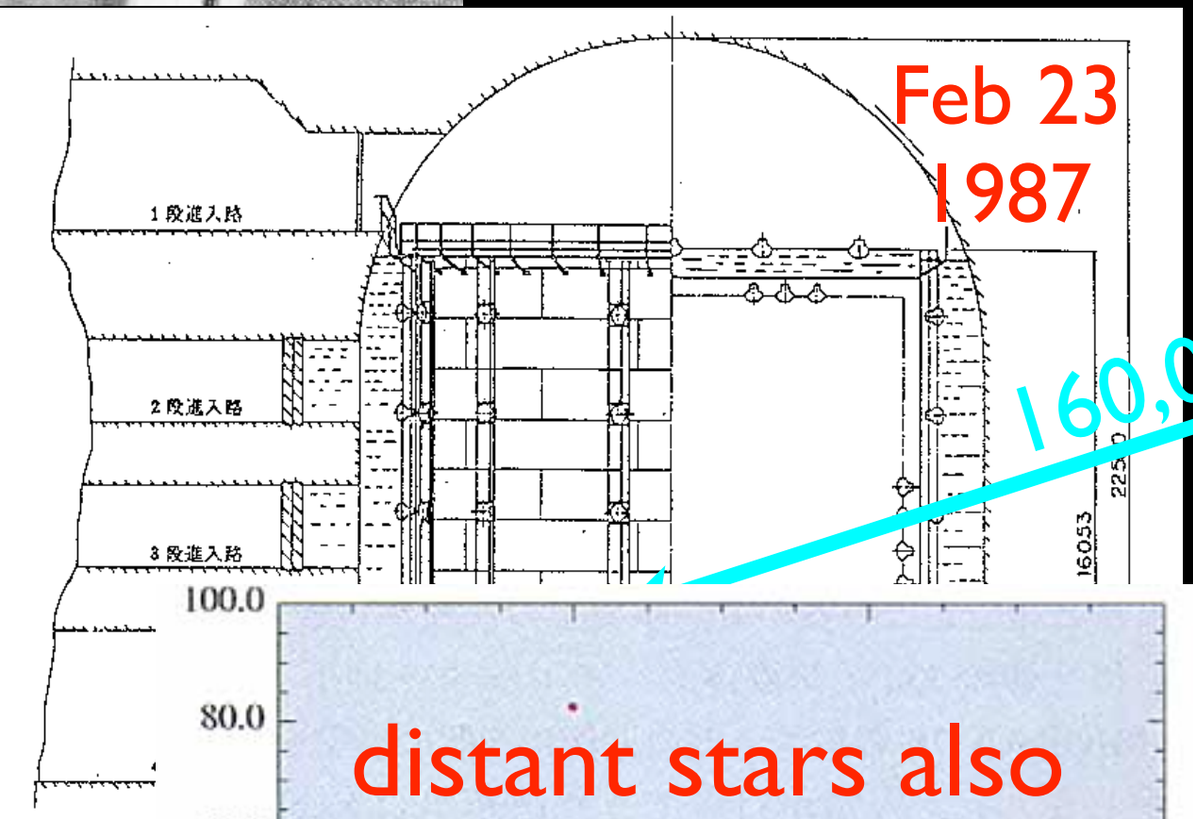
burning atoms in the Sun produces neutrinos
trillions through our body every second



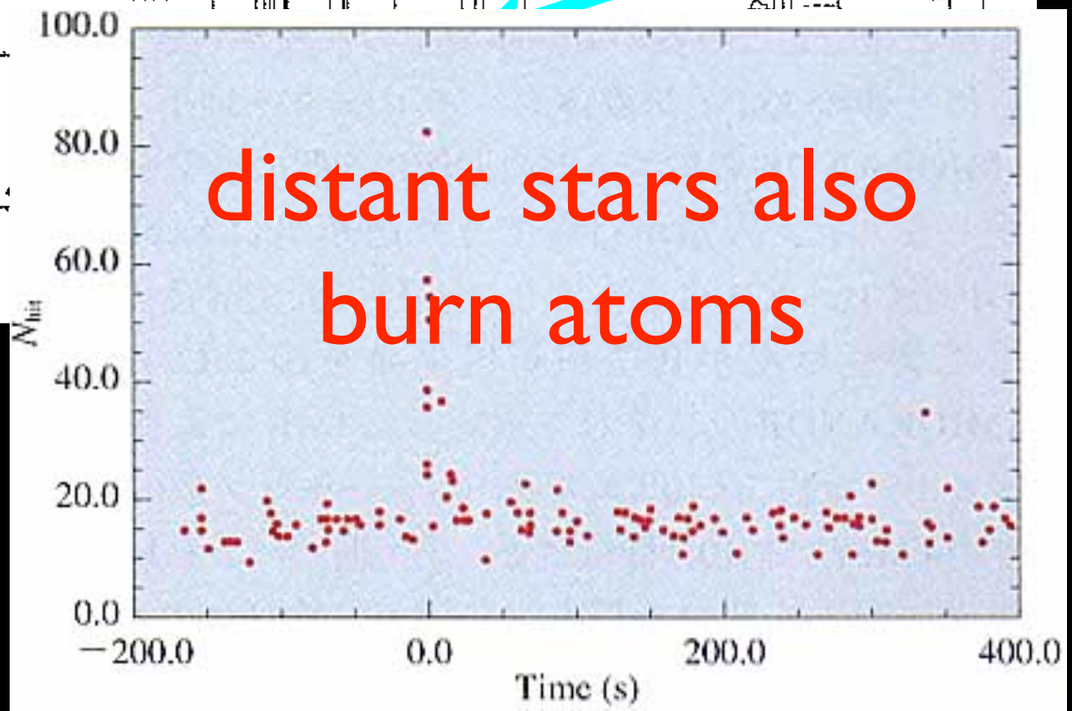




tremendous luck



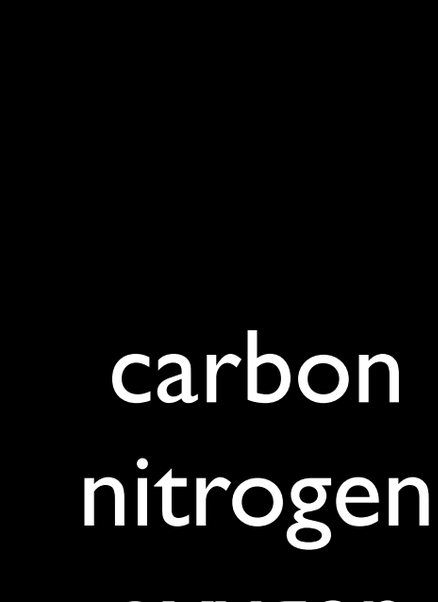
Feb 23
1987

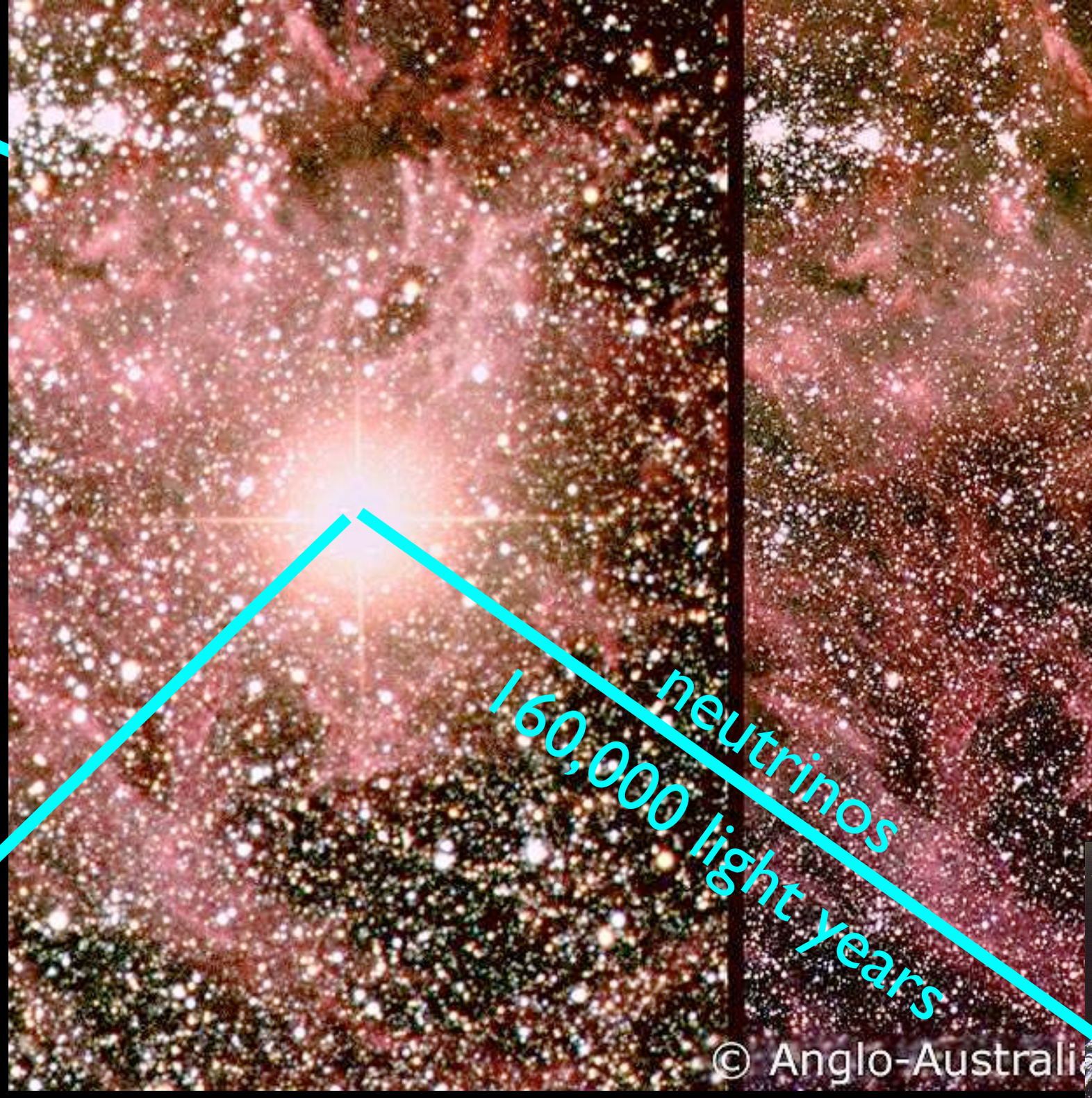


distant stars also
burn atoms

hydrogen
helium

carbon
nitrogen
oxygen
iron

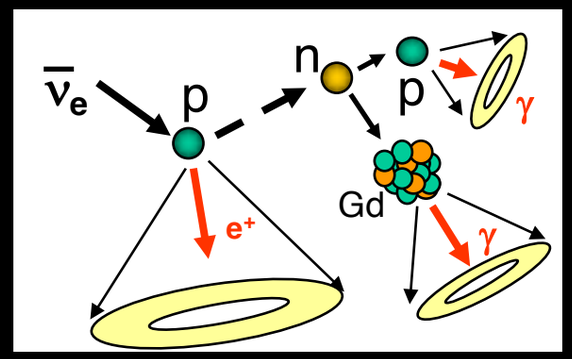




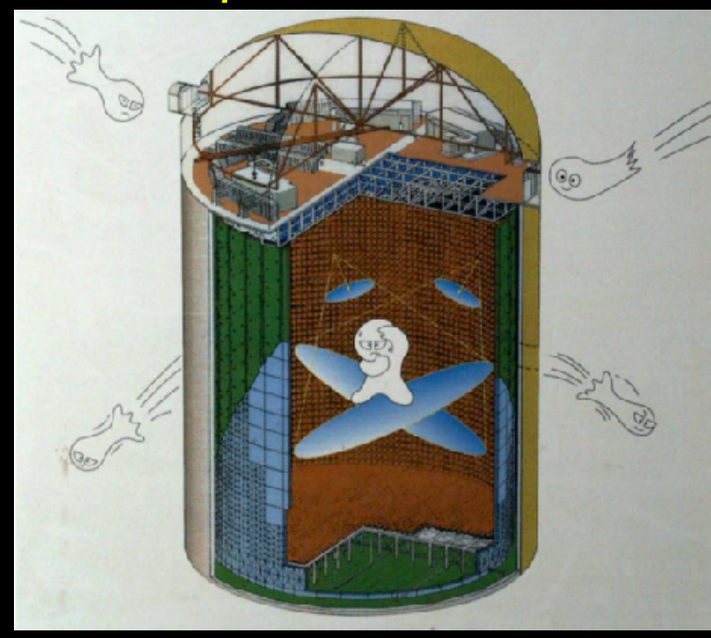
We are star dust

history supernova of explosions

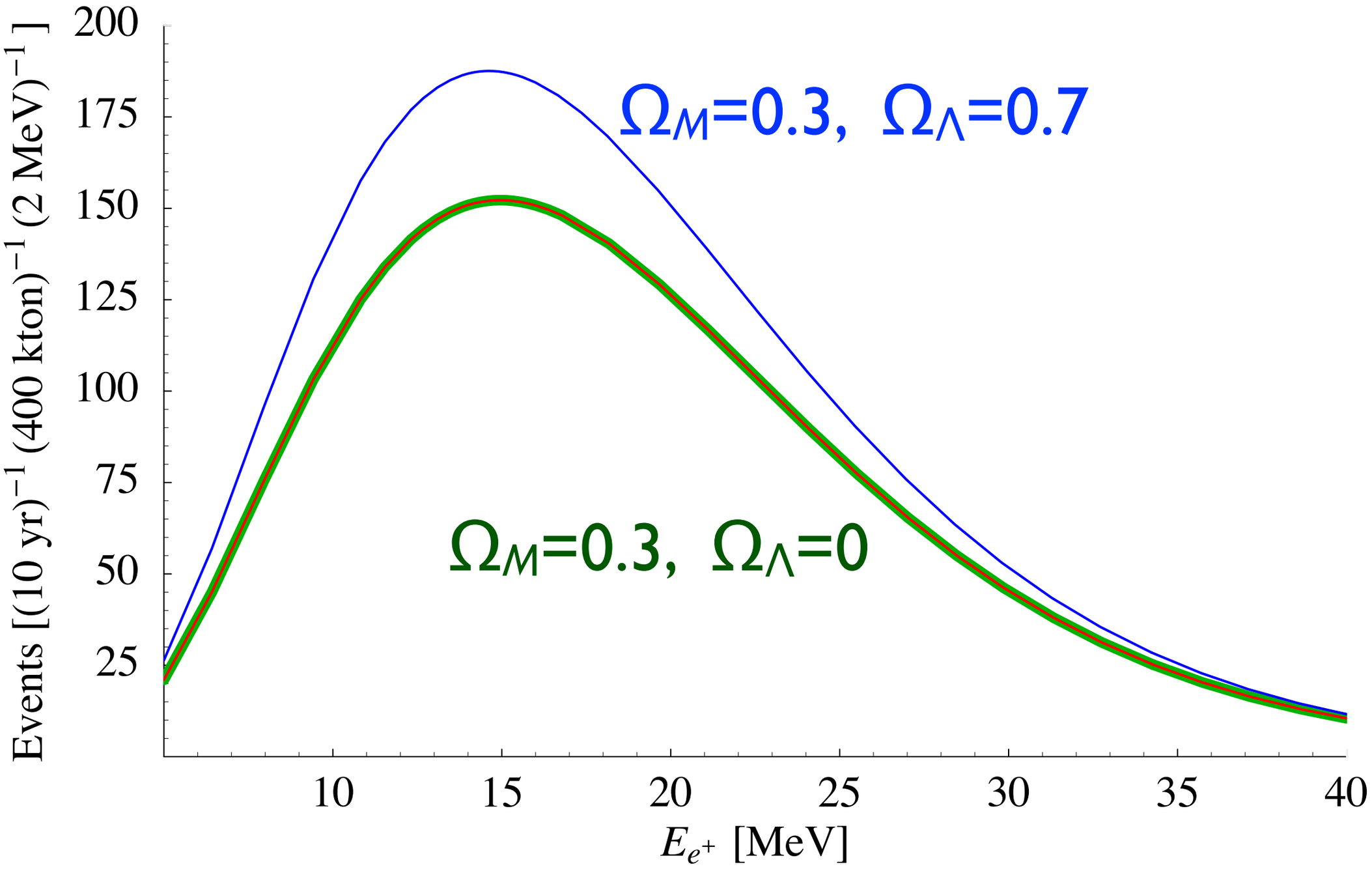
- need to understand the history of supernova explosions over the whole cosmic history
- Putting gadolinium into Super-K enhances the sensitivity
- can "see" neutrinos from billions of light years away
- Eventually even bigger experiment!



SuperKamiokande



even dark energy!



Hall, HM, Papucci, Perez, hep-ph/0607109

Outline

1. Where the elements come from → supernovae
2. How the stars were born
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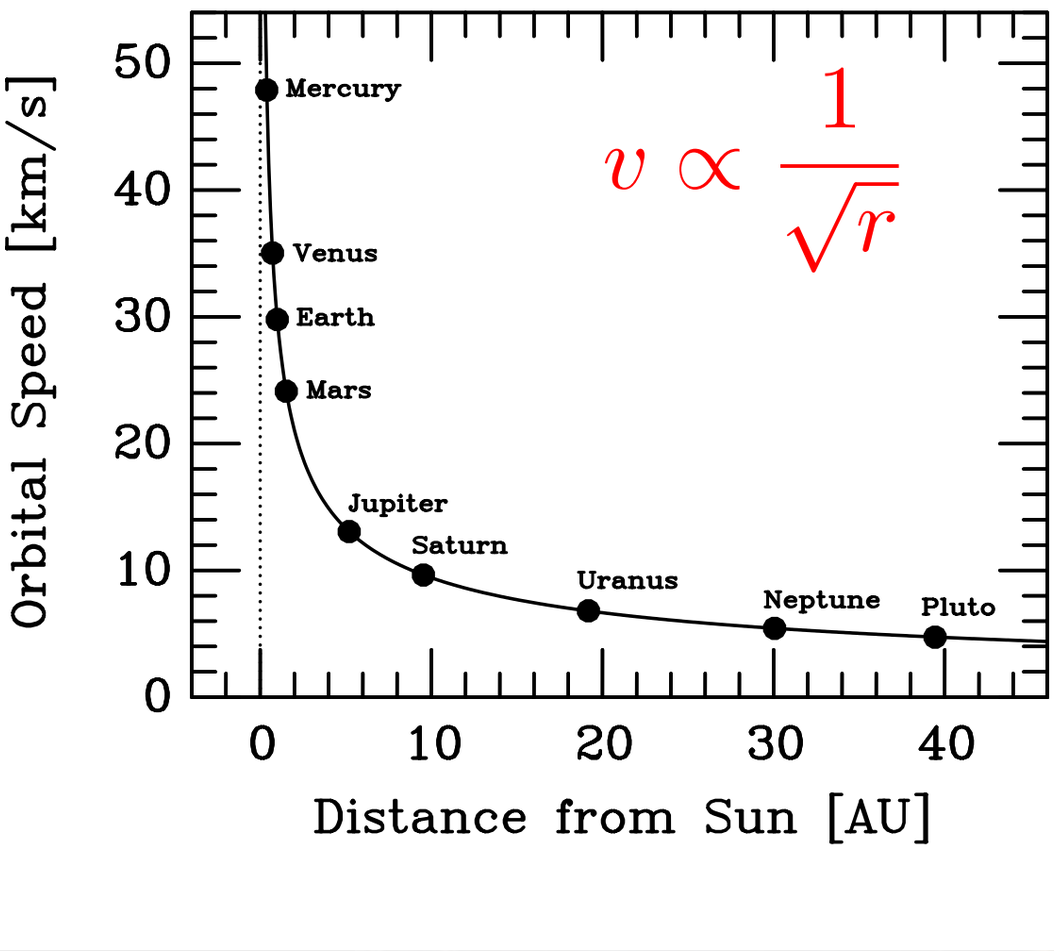
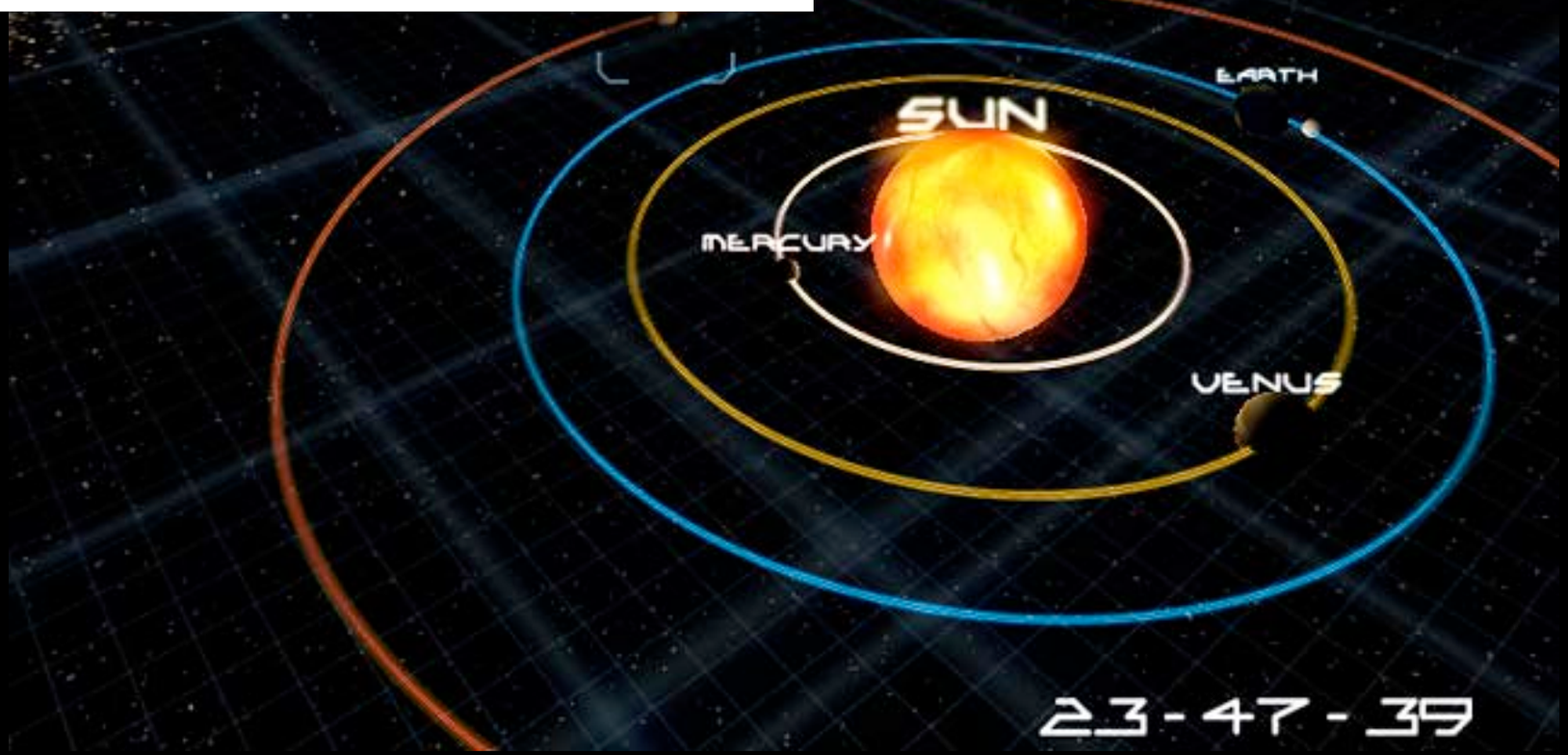
Outline

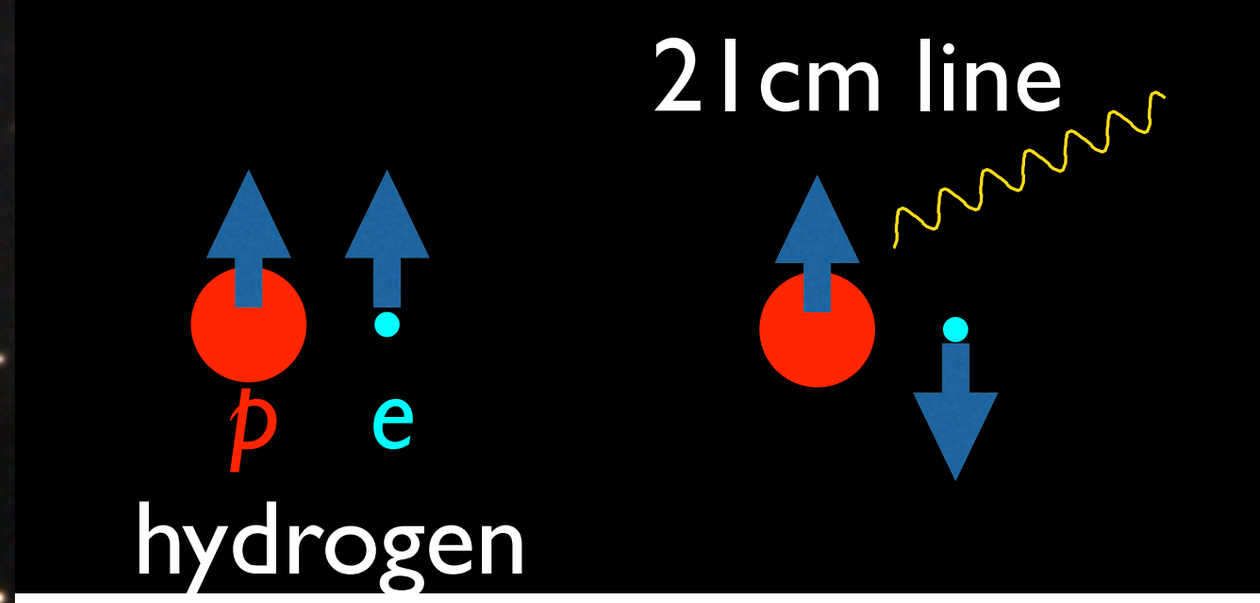
1. Where the elements come from → supernovae
2. How the stars were born → dark matter
3. Where the matter comes from

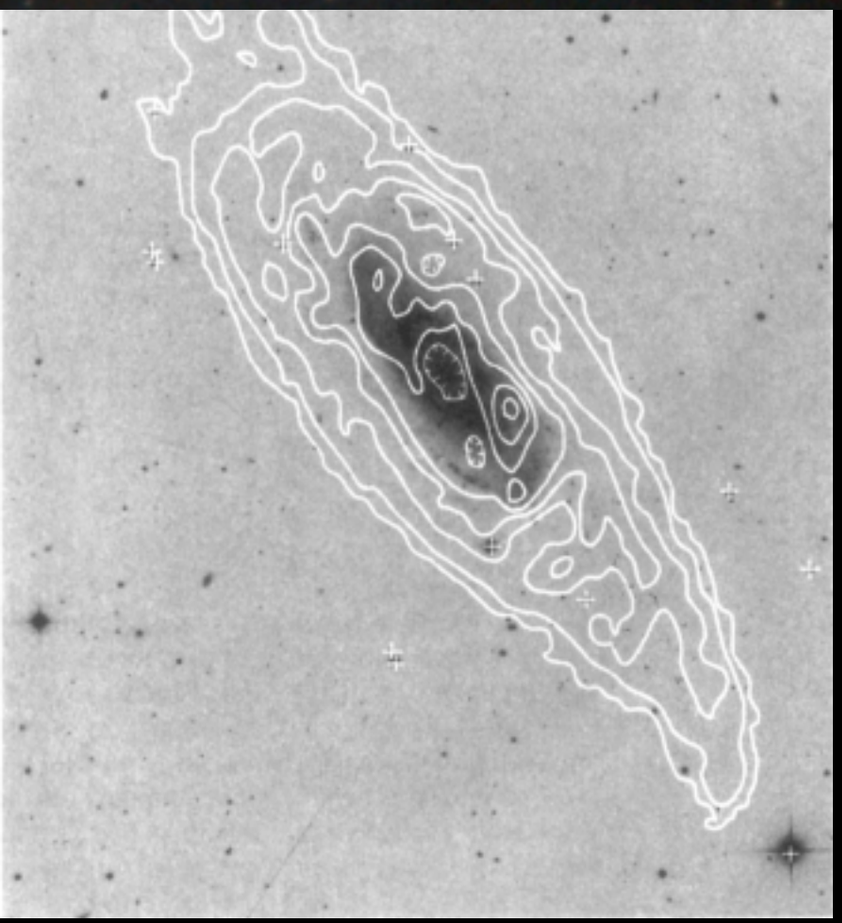
solar system

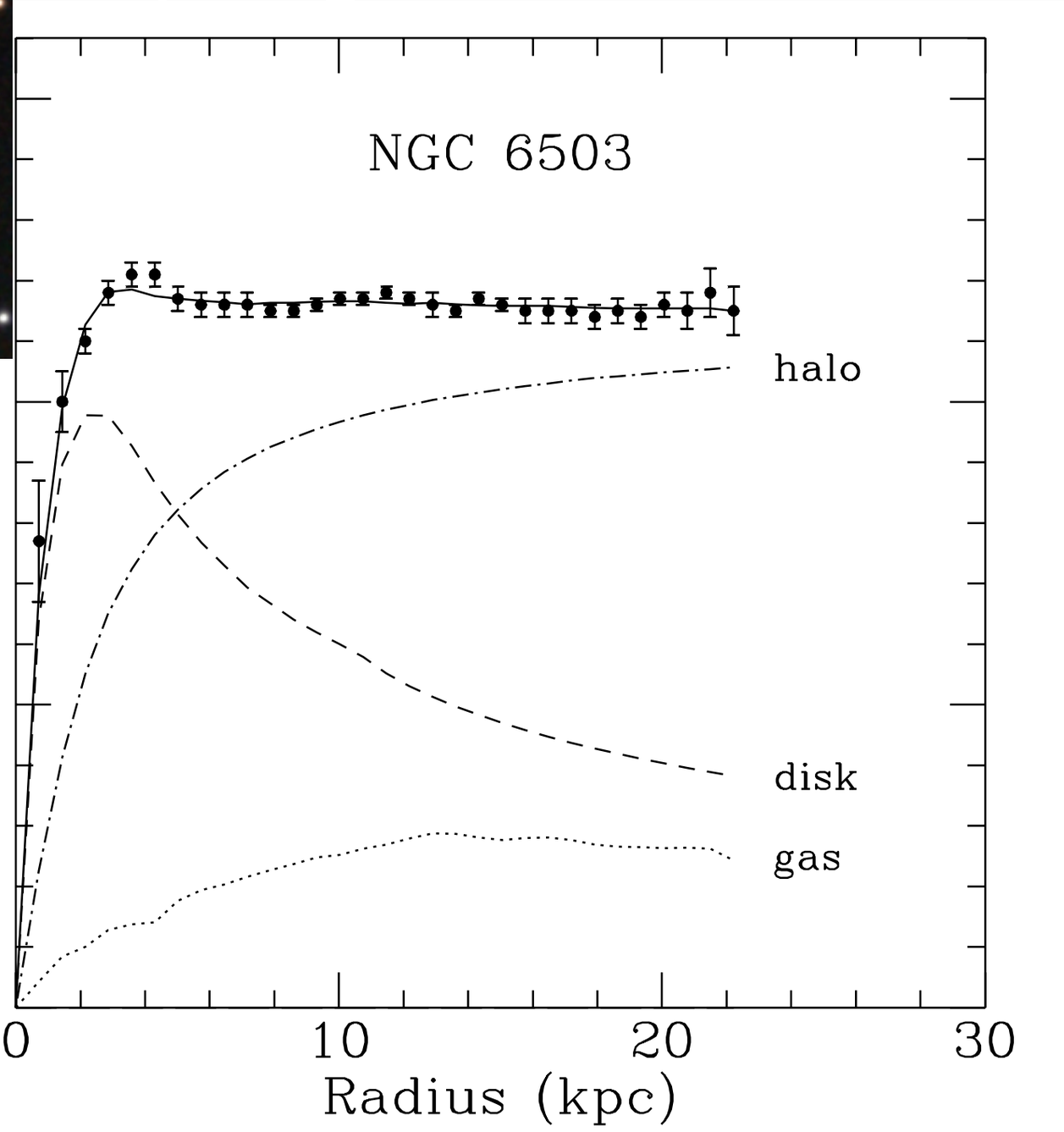




Earth revolves around the Sun at 30 km/s


21cm line
p
e
hydrogen




NGC 6503
halo
disk
gas
V_c (km s^{-1})
Radius (kpc)
0
50
100
0
10
20
30

Vera Rubin

1970's

true nature of galaxies

100k lyrs

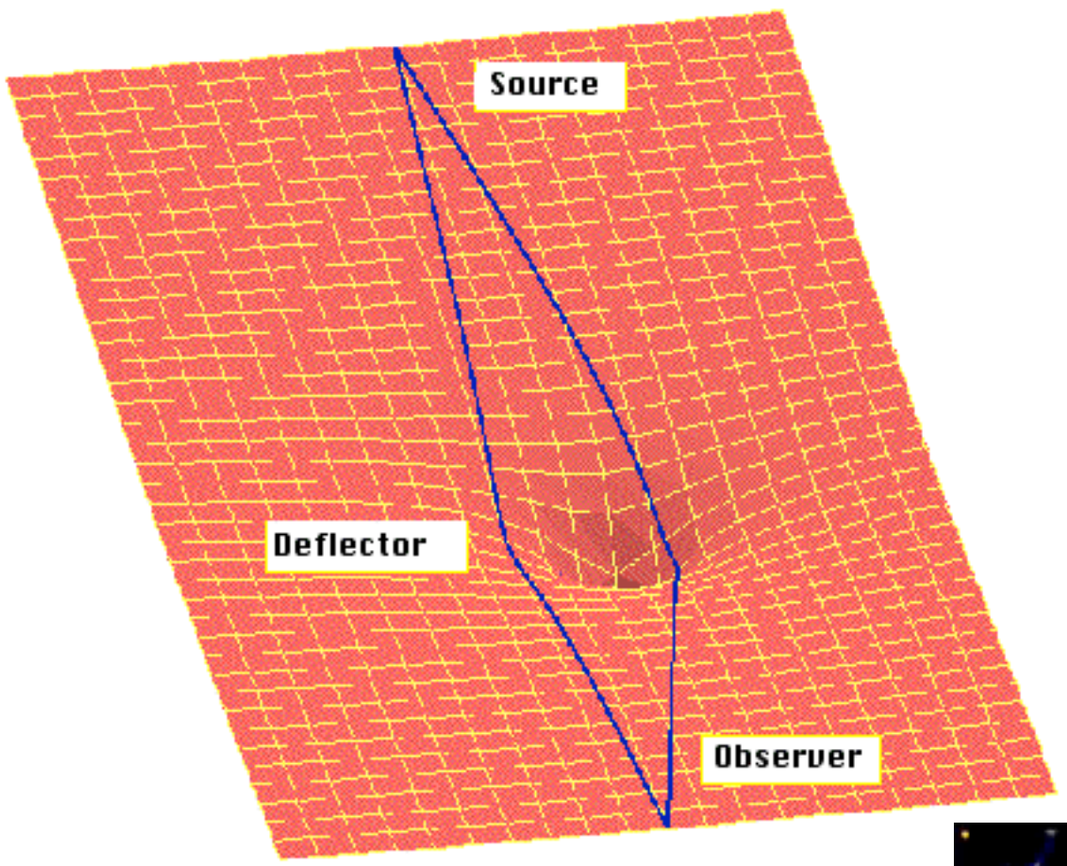
stars

dark matter

>M lyrs

cluster of galaxies

Abell 2218
2.1B lyrs



deflection angle
by a point lens

$$\Delta\theta = \frac{4G_N m}{c^2 r_c}$$

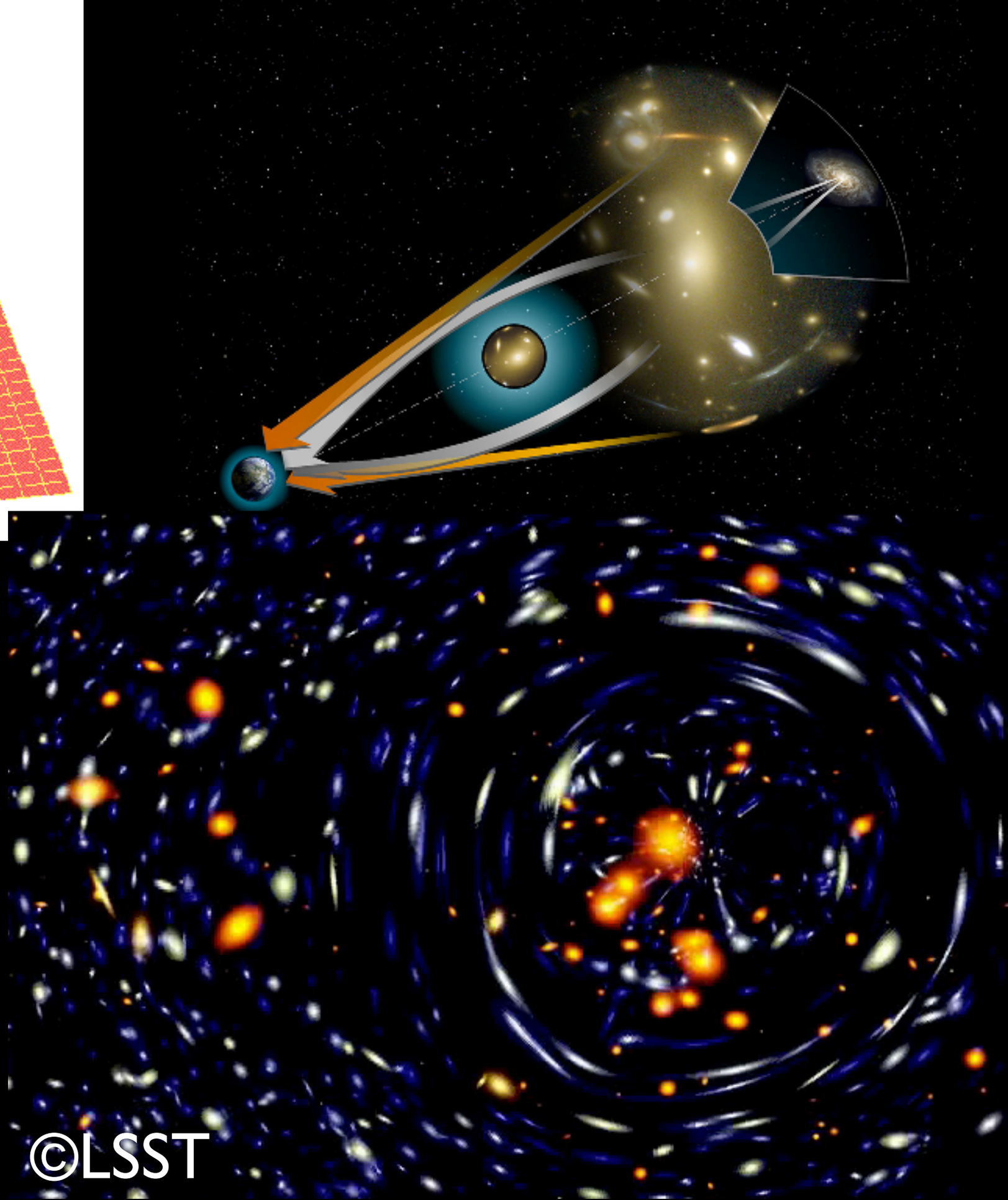
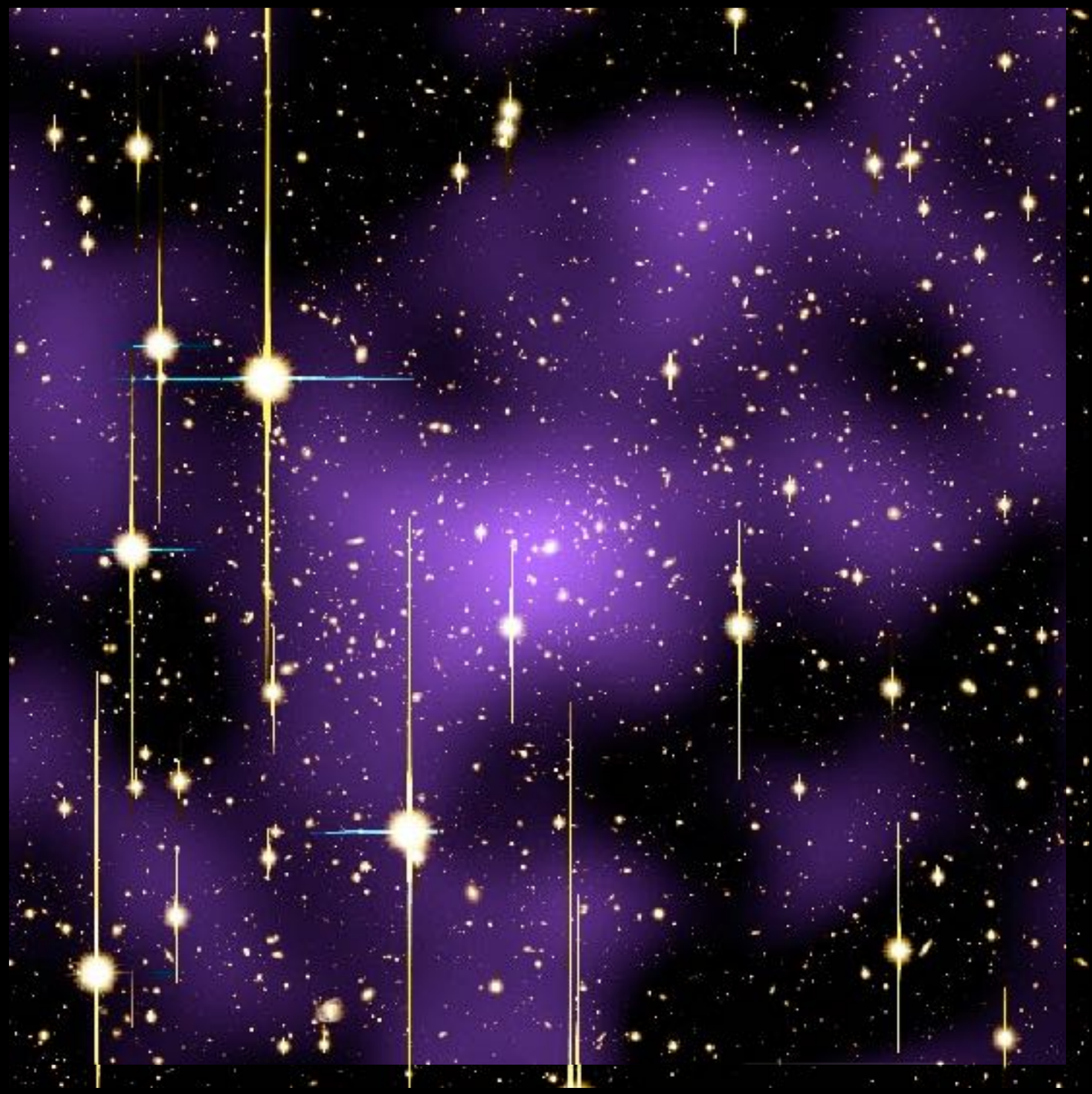


image invisible dark matter

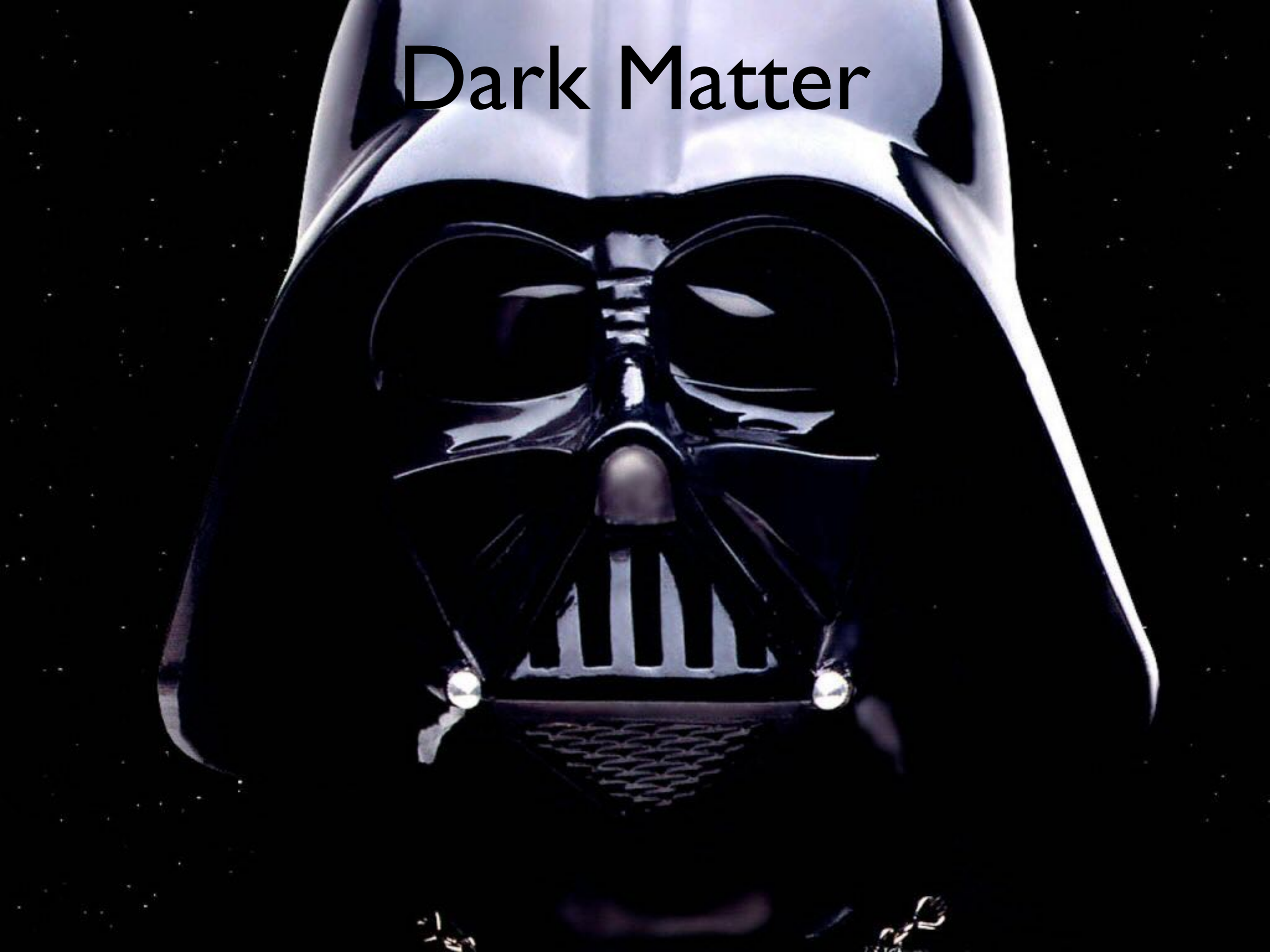


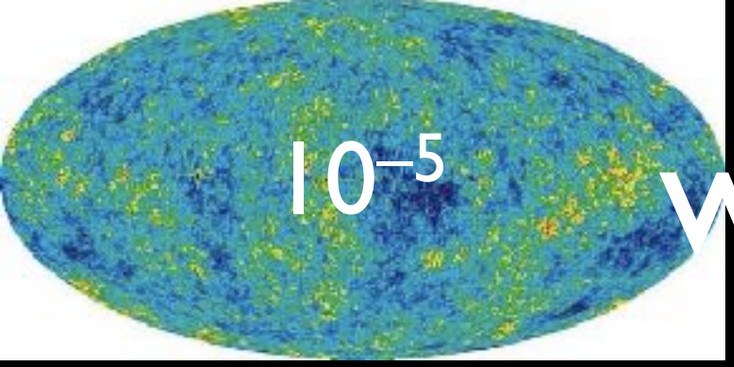
more than 80% of matter in the Universe is not atoms

Good not to be here

4B lyrs away

Dark Matter





we wouldn't exist without dark matter

without dark matter

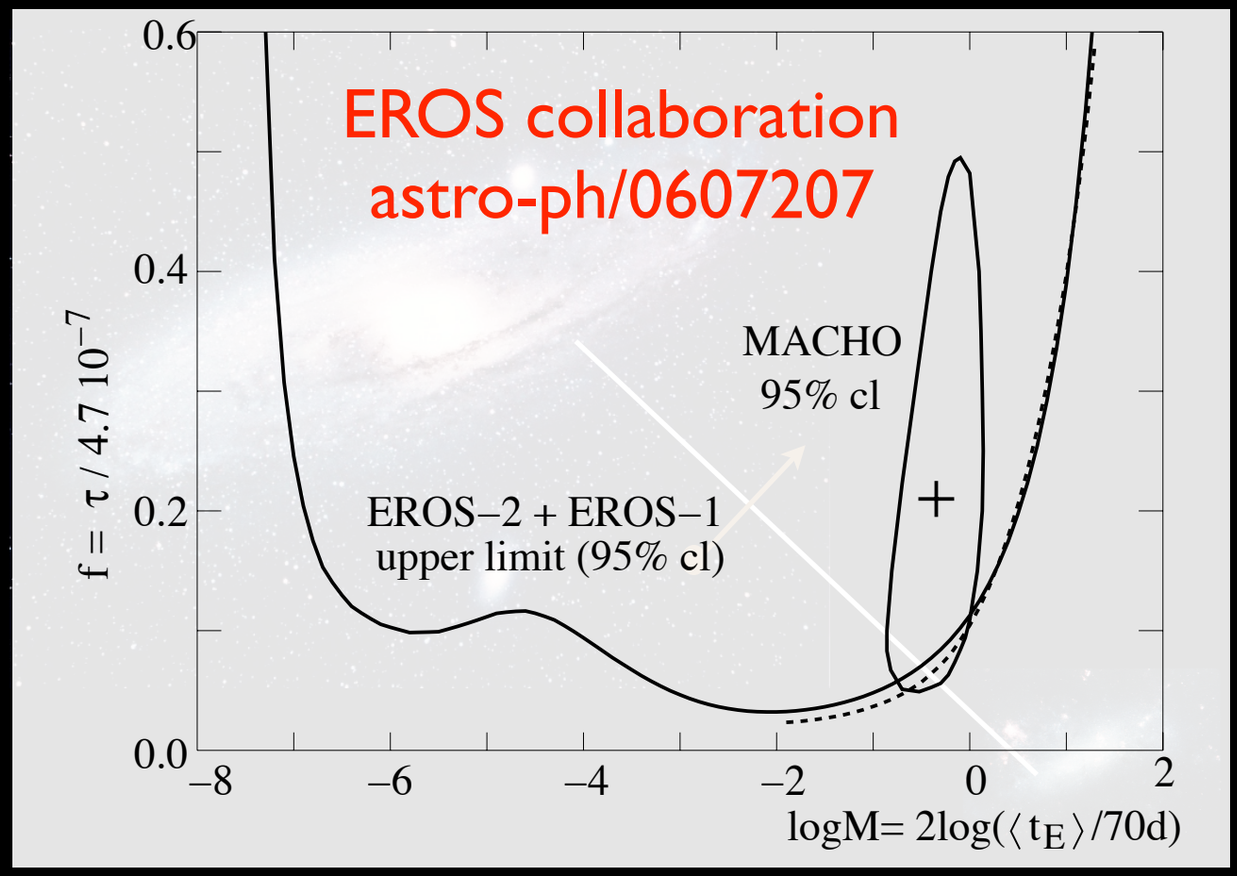
with dark matter

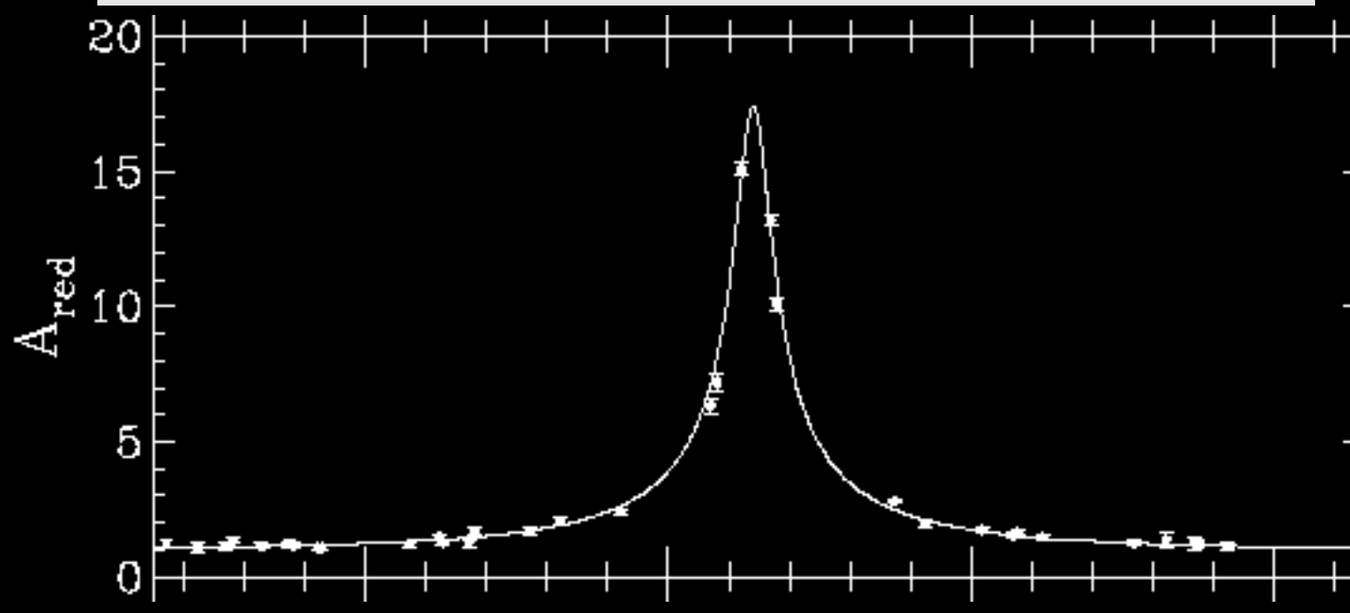
Reenacting the Big Bang with Cal Marching Band

Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)

Not enough of them!



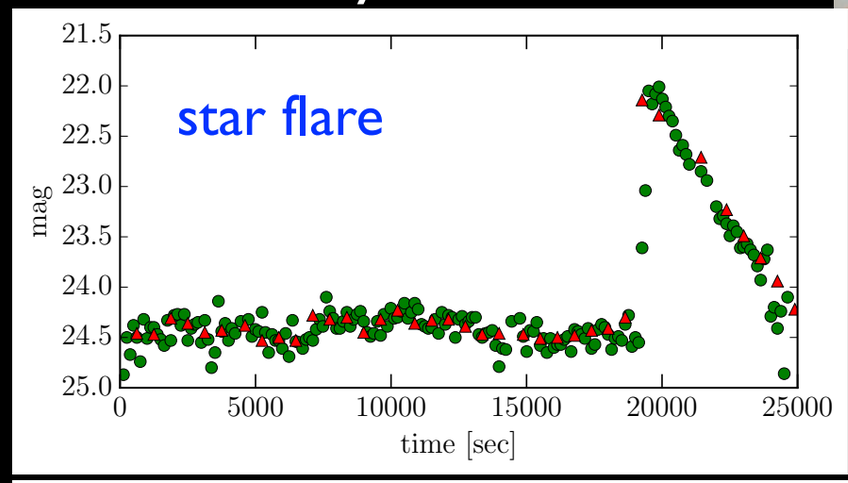


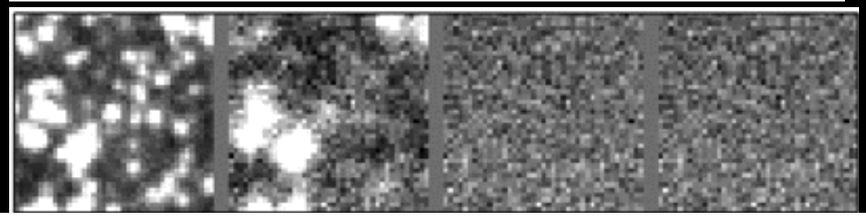
HSC result: Constraint on PBH

Niikura, MT et al., to submit soon

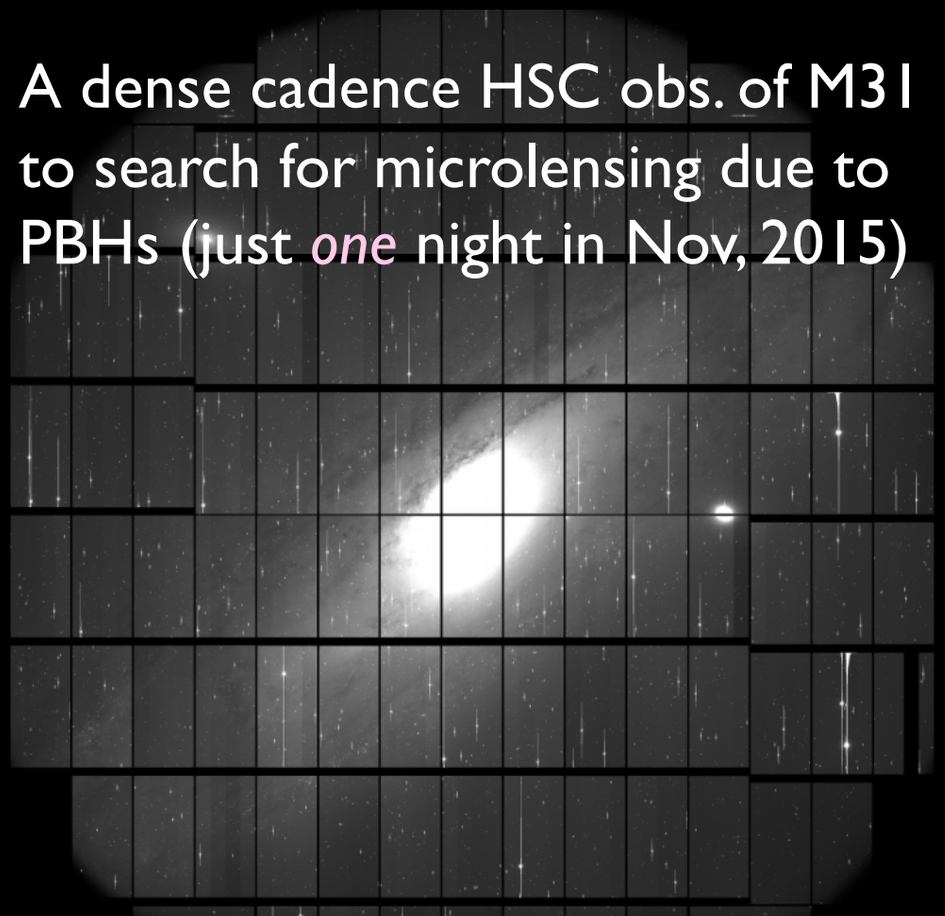
started from conversation with Hitoshi and Masahiro Kawasaki

Found many variable stars

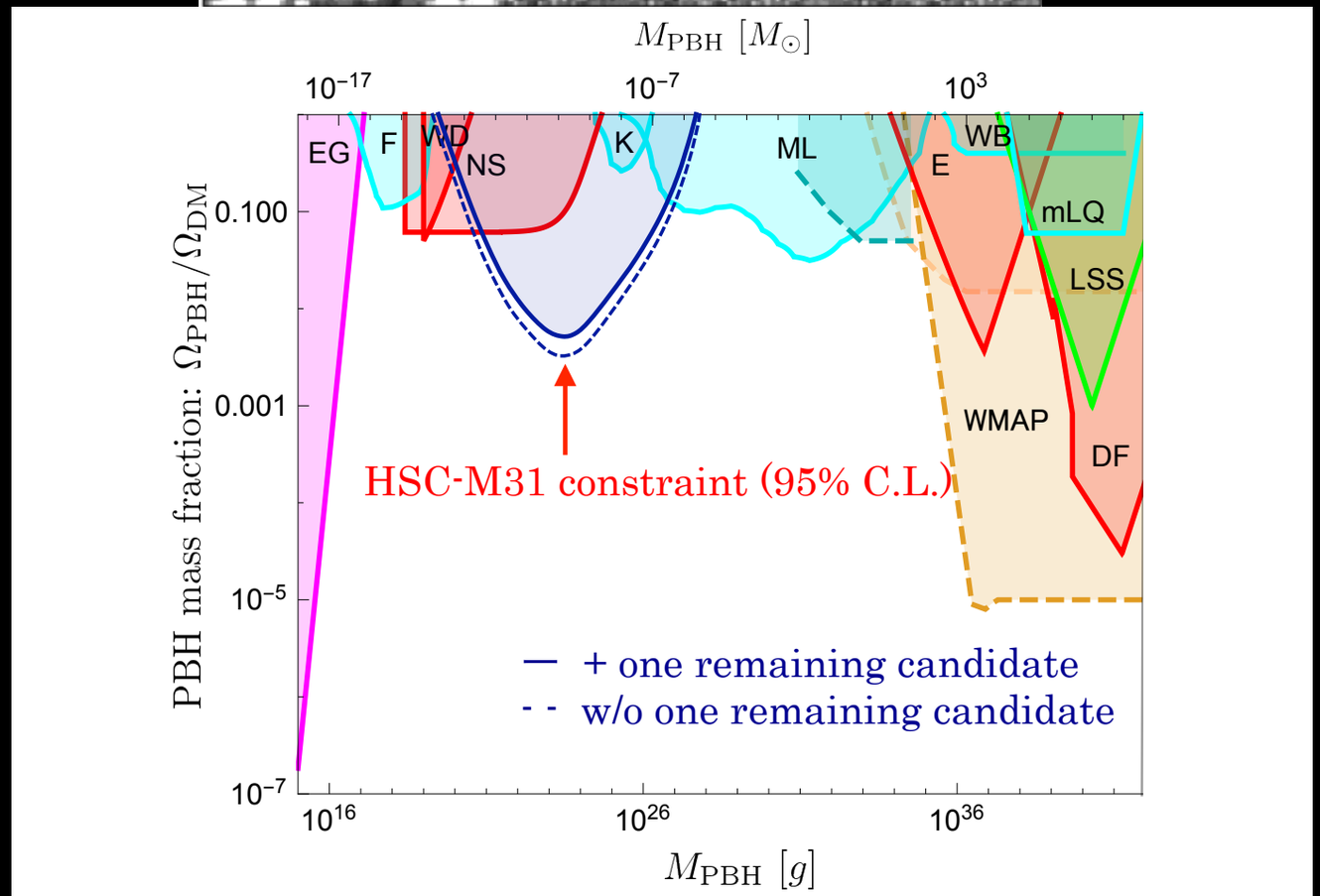




A dense cadence HSC obs. of M31 to search for microlensing due to PBHs (just *one* night in Nov, 2015)

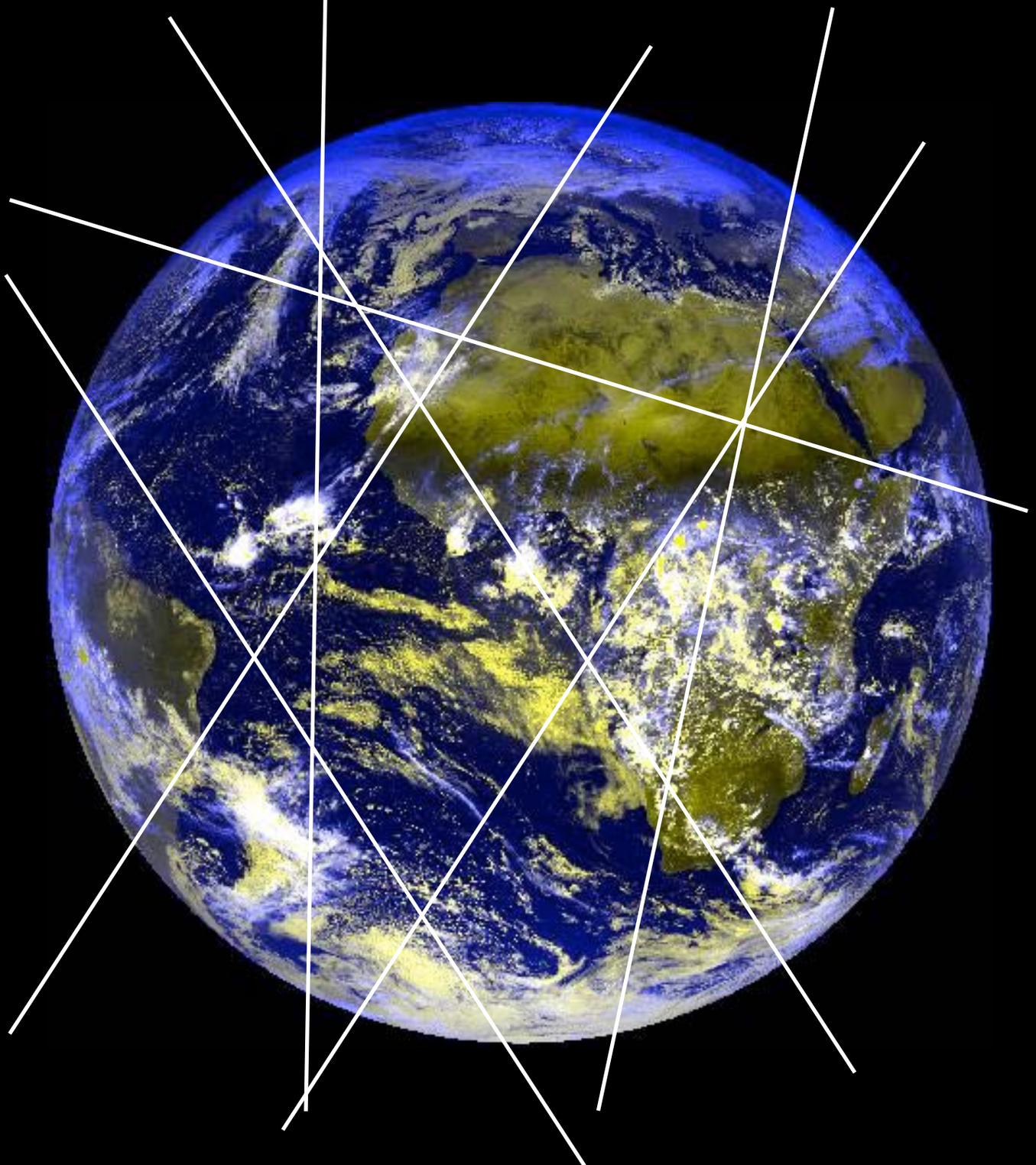


No detection ⇒ more stringent upper bound, than 2yr Kepler data (Griest et al.)



Masahiro Takada

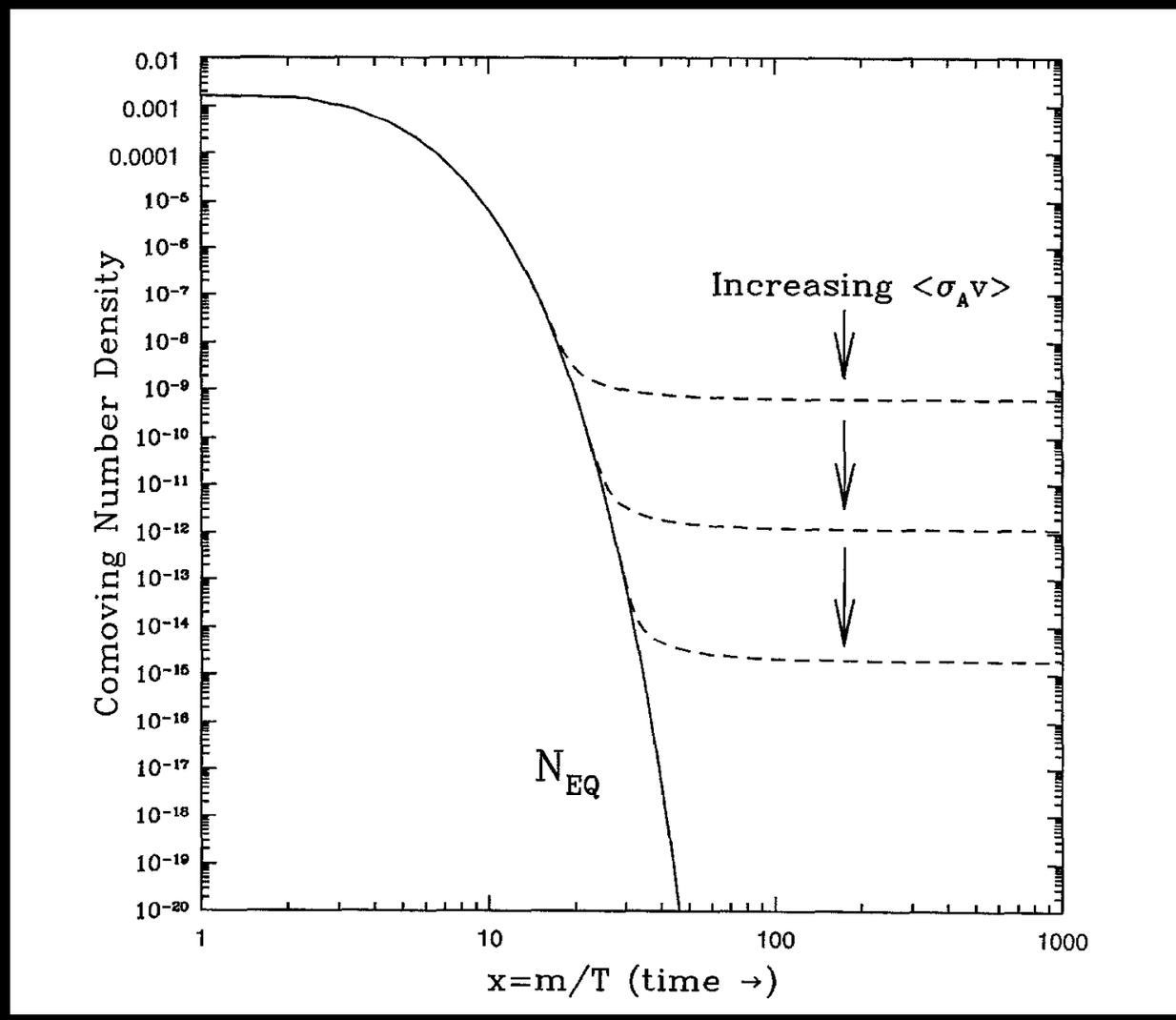
MACHO ⇒ WIMP



- It is probably WIMP (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation
- Will focus on WIMPs for the rest or the lecture

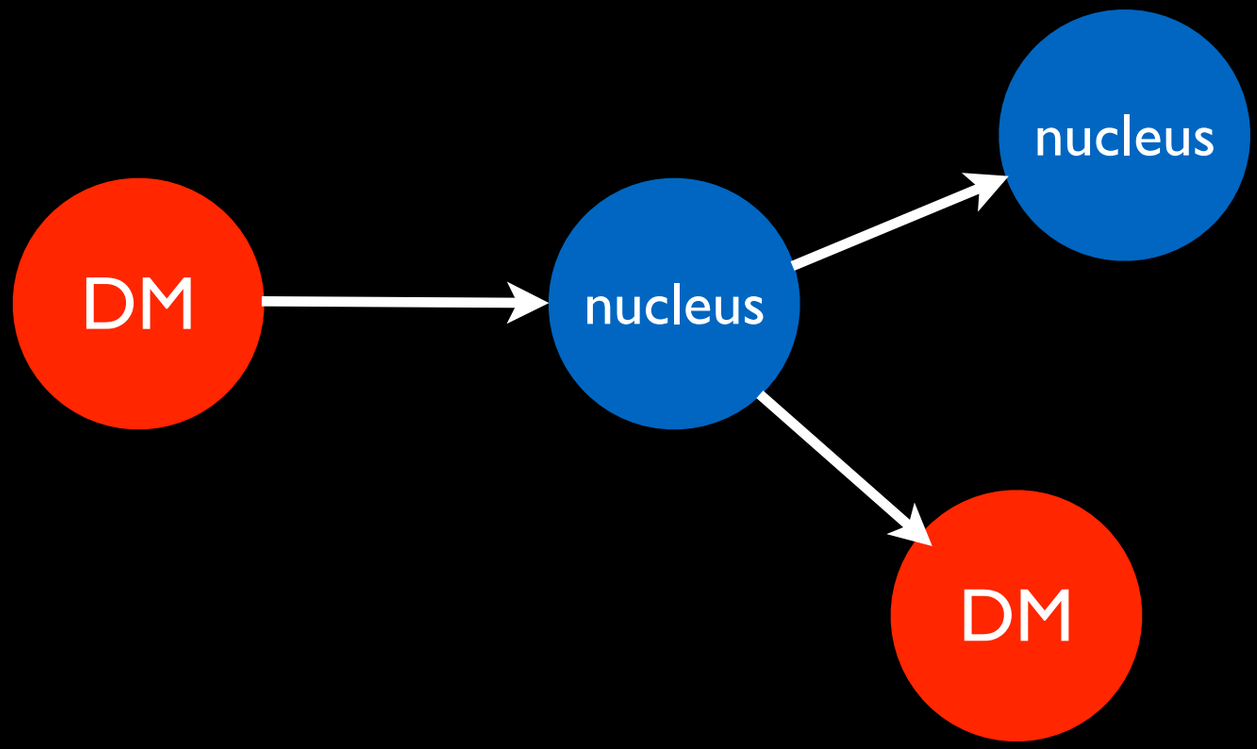
thermal relic

- thermal equilibrium when $kT > m_\chi c^2$
- Once $kT < m_\chi c^2$, no more χ created
- if stable, only way to lose them is annihilation
- but universe expands and χ get dilute
- at some point they can't find each other
- their number in comoving volume "frozen"



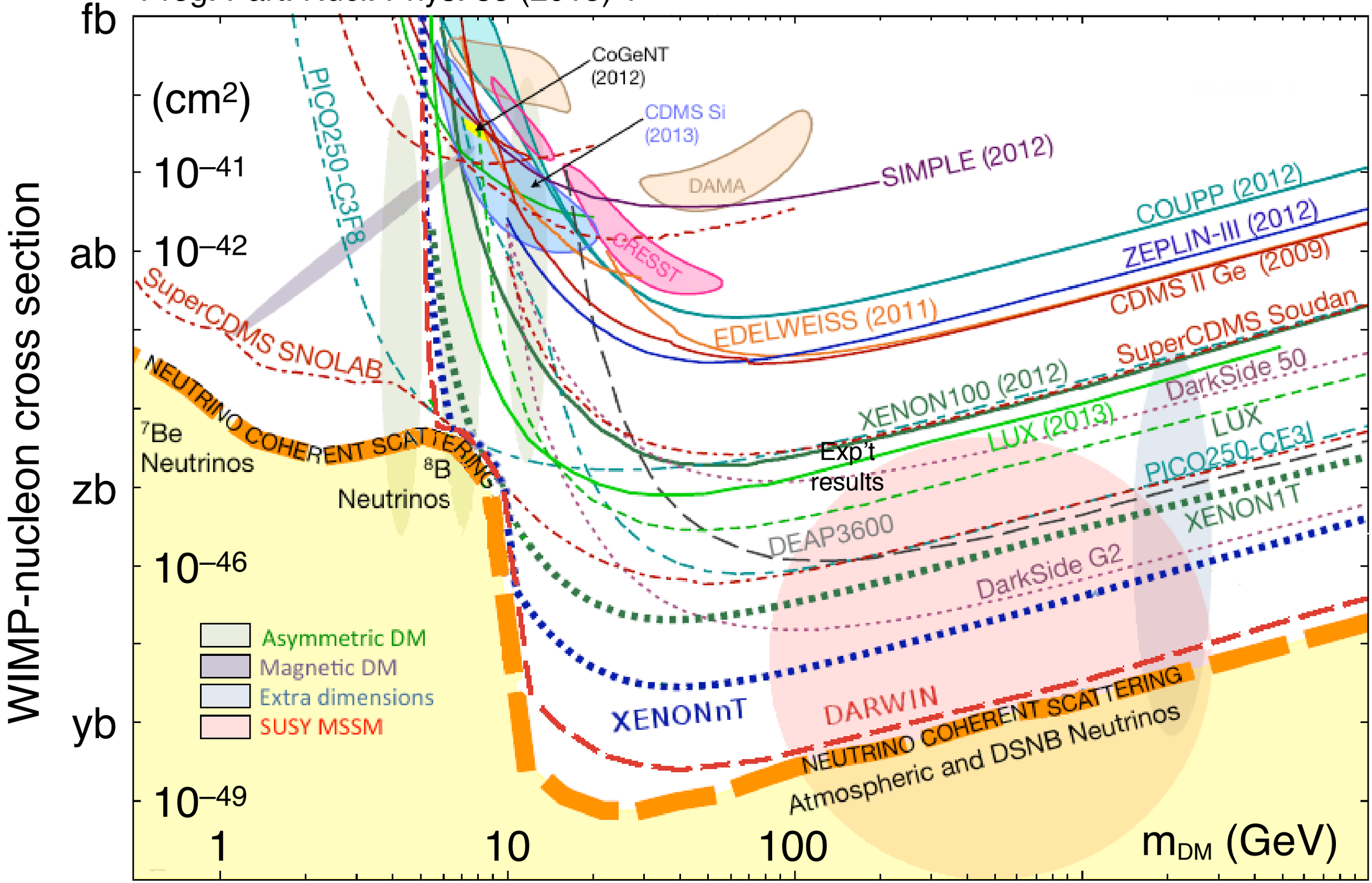
How do we look for it?

- maximum energy transfer to nucleus when $m_\chi \sim M_A$
- energy of the nucleus leads to a combination of
  - ionization
  - phonon
  - scintillation



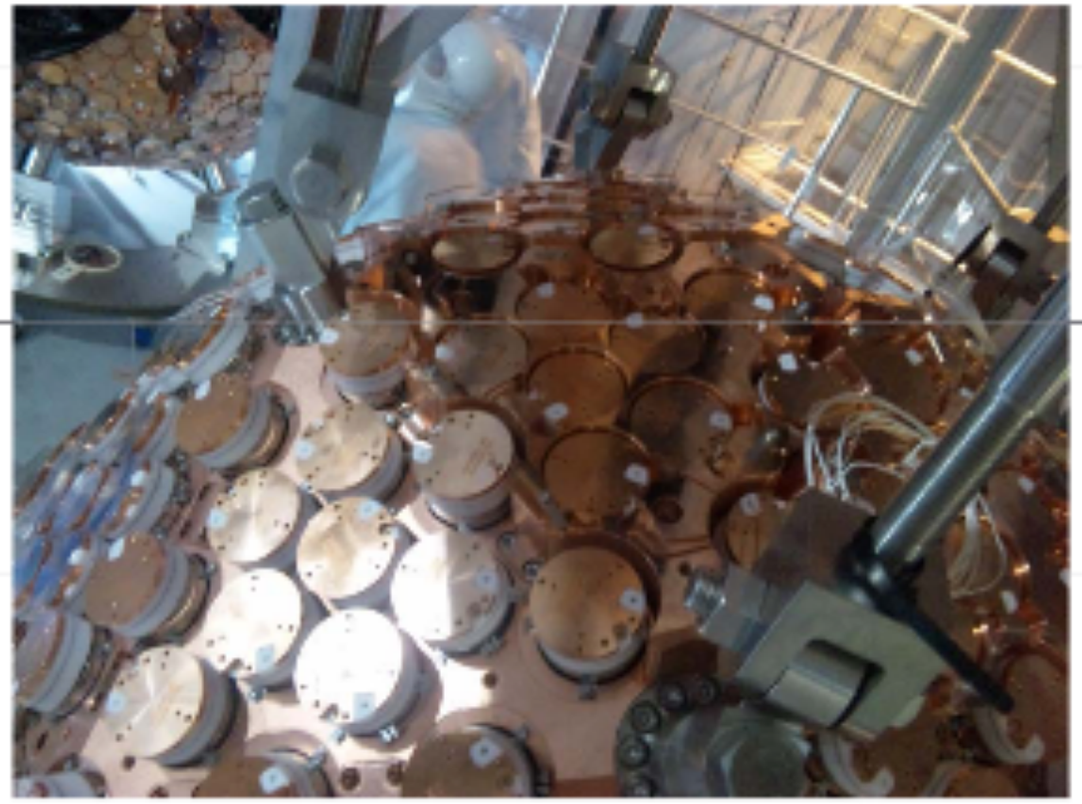
$$E_f = \frac{1}{2} m_\chi v_\chi^2 \frac{m_\chi M_A}{(m_\chi + M_A)^2} 2(1 - \cos\hat{\theta})$$

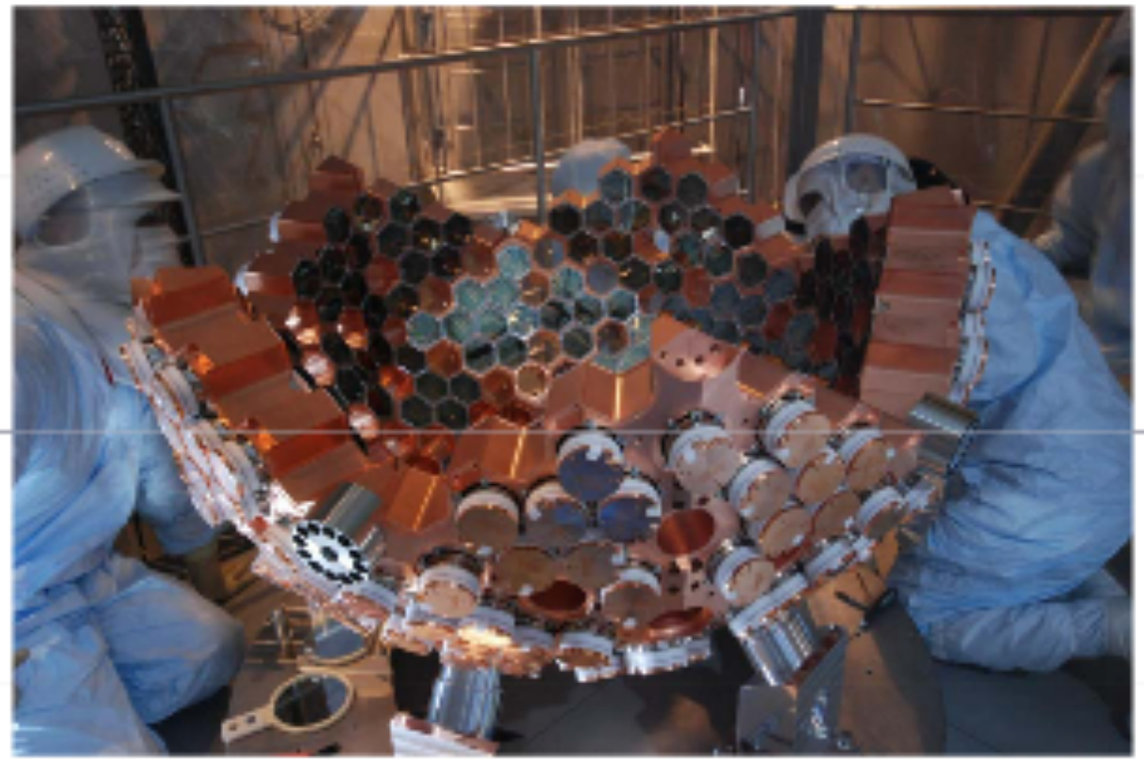
Prog. Part. Nucl. Phys. 85 (2015) 1




63

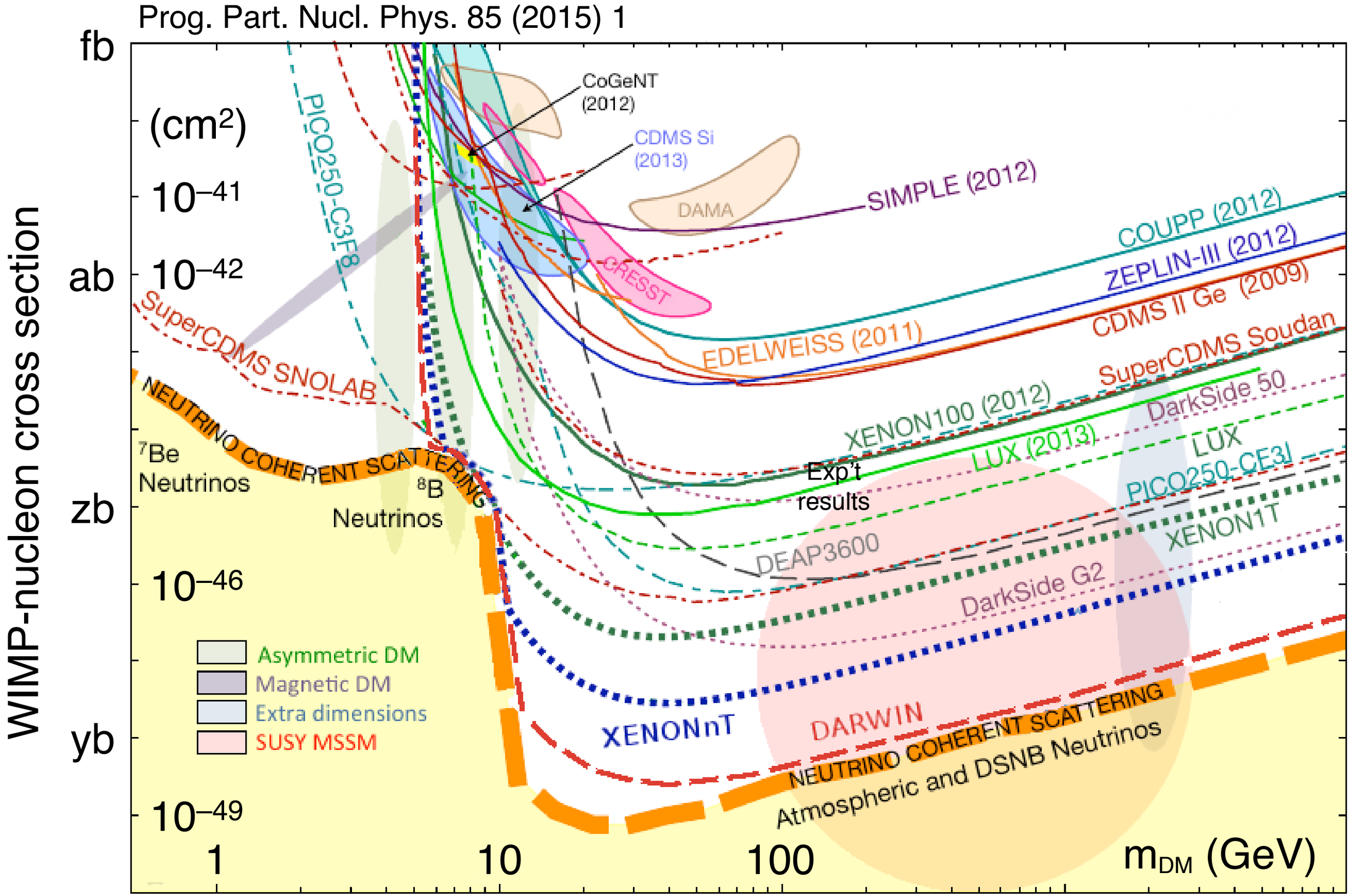
December-24, 2009





XMASS

1t liquid Xenon
in Kamioka mine


Prog. Part. Nucl. Phys. 85 (2015) 1
WIMP-nucleon cross section
fb
(cm²)
10⁻⁴¹
ab
10⁻⁴²
zb
10⁻⁴⁶
yb
10⁻⁴⁹
1
10
100
m_DM (GeV)
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
PICO250-C3F8
SuperCDMS SNOLAB
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
XENON100 (2012)
DarkSide 50
LUX (2013)
LUX
PICO250-CF3I
Exp't results
DEAP3600
XENON1T
DarkSide G2
XENONnT
DARWIN
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
⁷Be Neutrinos
NEUTRINO COHERENT SCATTERING
⁸B Neutrinos
Asymmetric DM
Magnetic DM
Extra dimensions
SUSY MSSM

History of the Universe

ten-billionth sec

3min

380k yrs

13.8Bzyrs

Accelerators
LHC
Tevatron
RHIC

high-energy cosmic rays

Inflation

BIG BANG

possible dark matter relicts

DM

CMB

cosmic microwave radiation visible

t	10^{-44}	10^{-37} s		10^{-10} s		10^{-5} s		10^{2} s		3×10^{5} y		10^{9} y		12×10^{9} y		(sec,yrs)
T	10^{32}	10^{28}		10^{15}		10^{12}		10^{9}		3000		15		2.7		(Kelvin)
E	10^{19}	10^{15}		10^{2}		10^{-1}		10^{-4}		3×10^{-10}		10^{-12}		2.3×10^{-13}		(GeV)

Today

Key:

- q quark
- g gluon
- e electron
- μ muon τ tau
- ν neutrino
- W, Z bosons
- qq meson
- qqq baryon
- ion
- atom
- photon
- galaxy
- star
- black hole

Outline

1. Where the elements come from → supernovae
2. How the stars were born → dark matter
3. Where the matter comes from

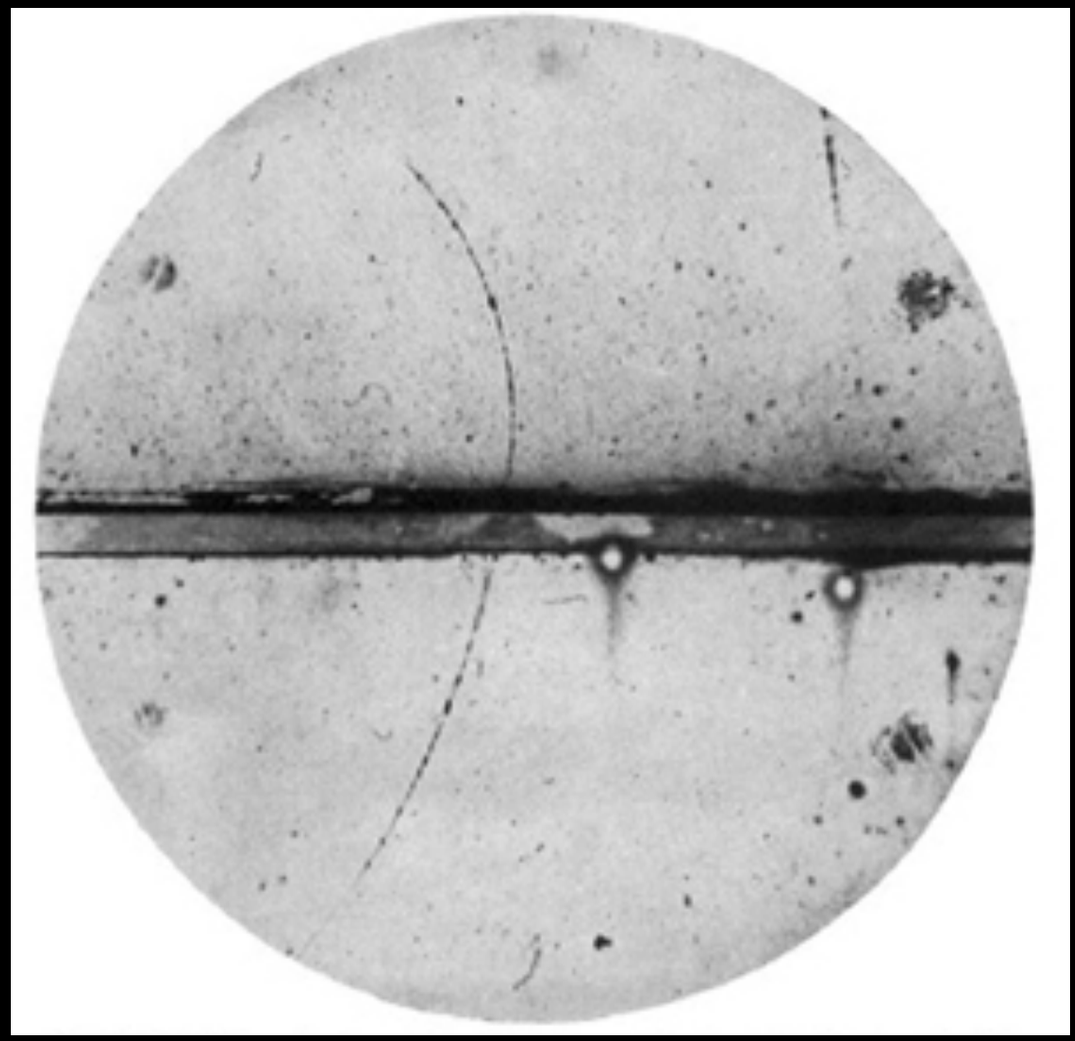
Outline

1. Where the elements come from → supernovae
2. How the stars were born → dark matter
3. Where the matter comes from → neutrinos?

Anti-matter!

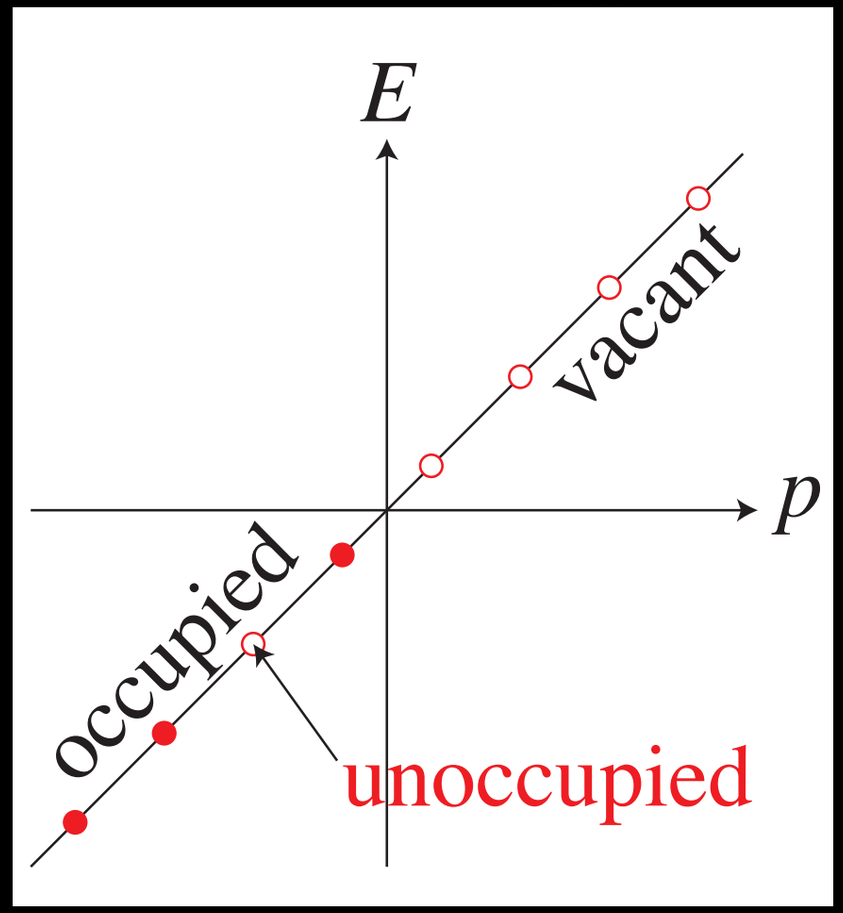
Carl Anderson

1936 Nobel Prize in Physics



Dirac equation

- Dirac forced a marriage between quantum mechanics and special relativity
- equation he discovered has negative energy solutions
- assume they are all *occupied*
- Then a *hole* would be a particle of opposite charge



Anti-Matter

- for every particle, there is an anti-particle
  - CPT theorem in Quantum Field Theory
- same mass, same lifetime
- opposite electric charge, helicity
- electron e^- and positron e^+
- proton p and anti-proton $\overline{p}$
- neutron n and anti-neutron $\overline{n}$

Irène

Frédéric Joliot-Curie

e−
electron

e+
positron

γ
photon

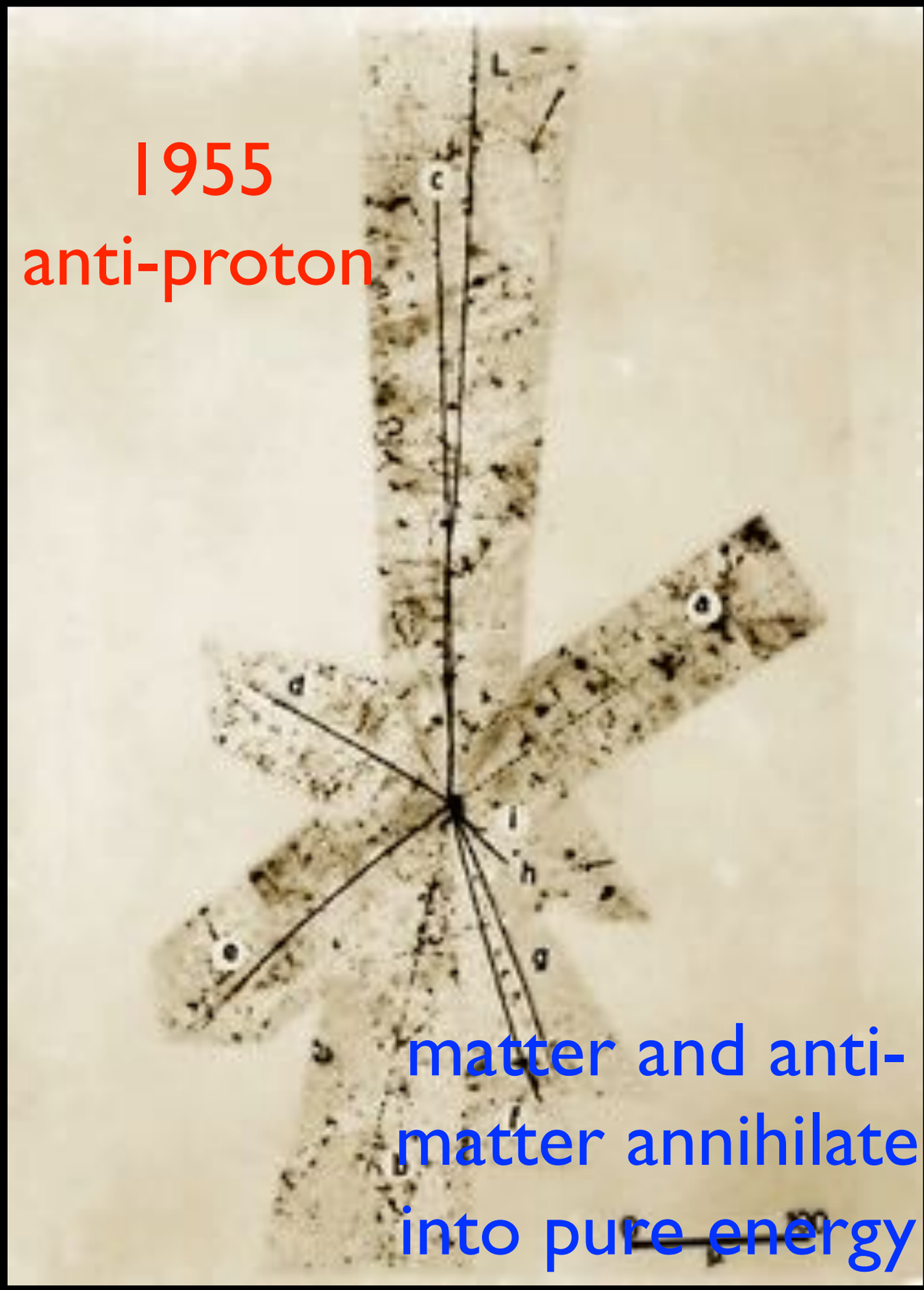
1933
first human-made anti-matter

Berkeley

Emilio Owen

Segrè Chamberlain

1955
anti-proton

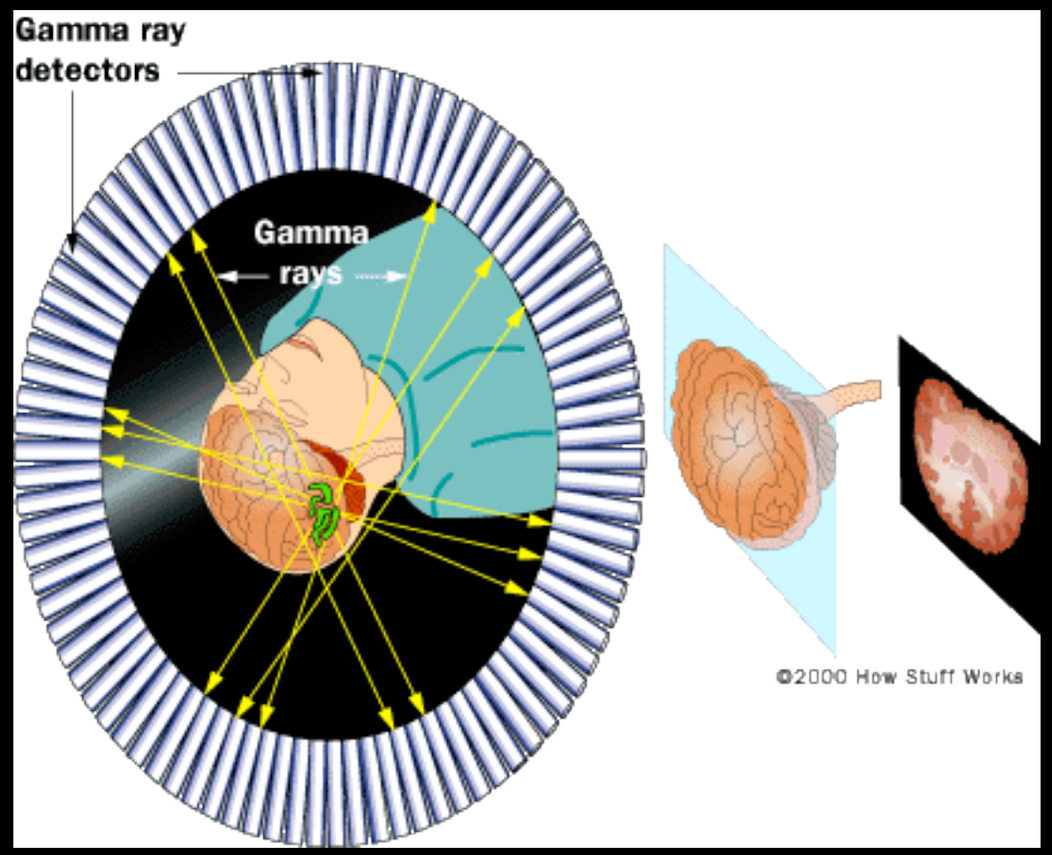


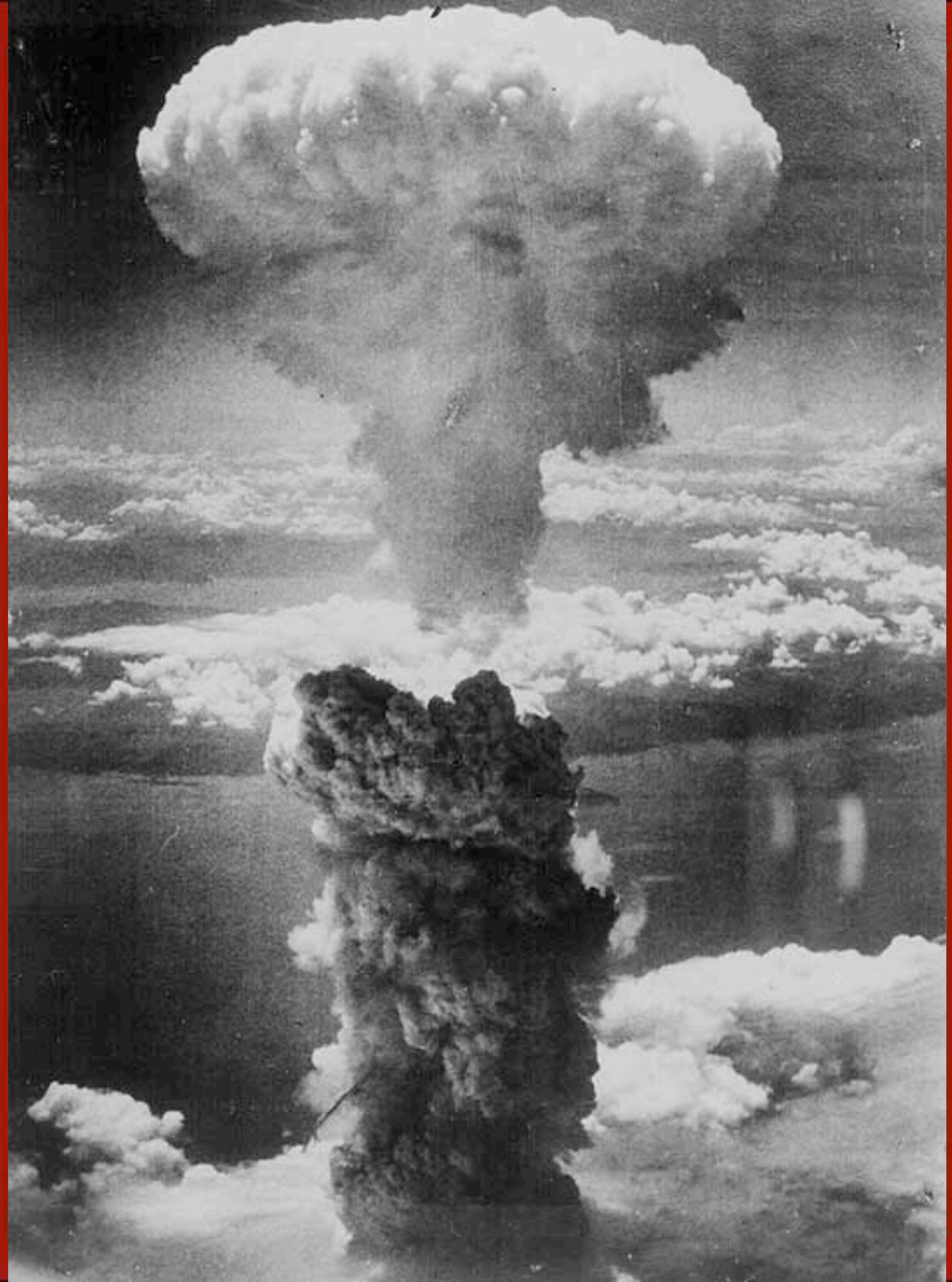
matter and anti-matter annihilate into pure energy

anti-matter at use

Positron Emission Tomography (PET)

Lawrence Berkeley
National Laboratory

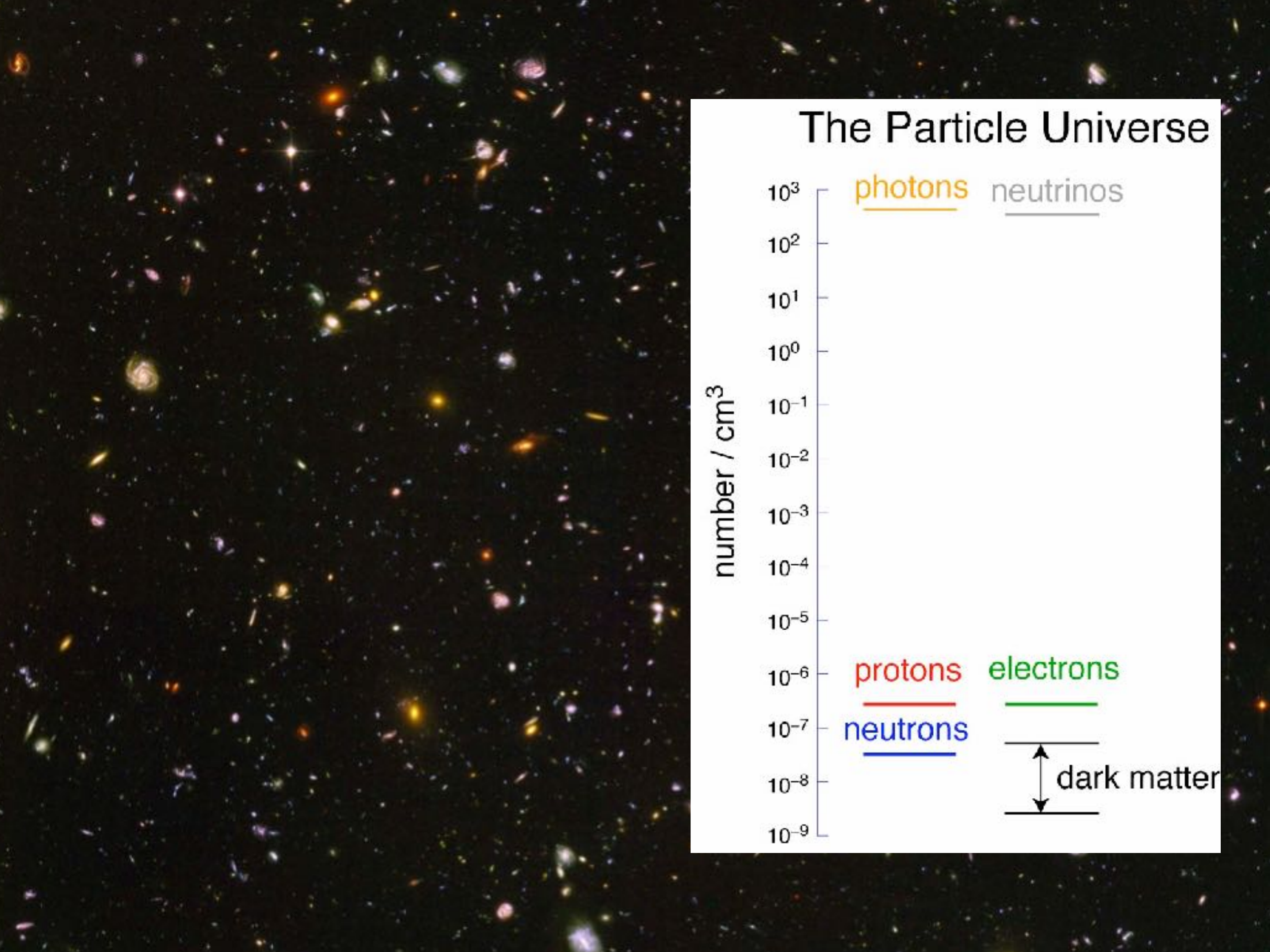


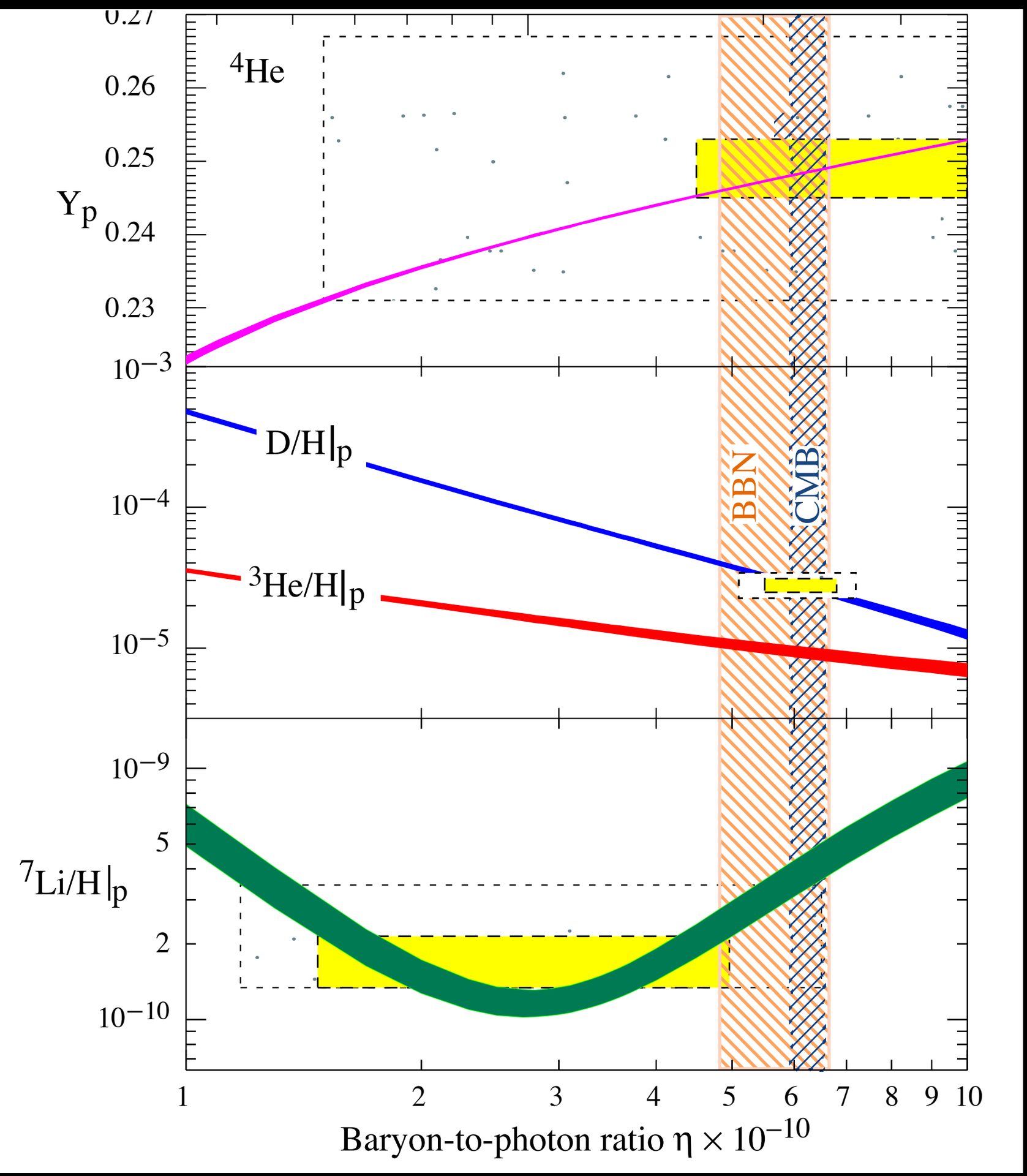


- European Laboratory CERN
- A scientist produced a quarter gram of anti-matter without the knowledge of the Director General
- *falls into wrong hands!*

billion trillion trillion dollars

Anti-Matter


The Particle Universe
photons
neutrinos
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
number / cm^3
protons
electrons
neutrons
dark matter



$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

Early Universe

1,000,000,002

1,000,000,000

matter

anti-matter

Current Universe

2 : us

matter *anti-matter*

We won! But *why*?

Beginning of Universe

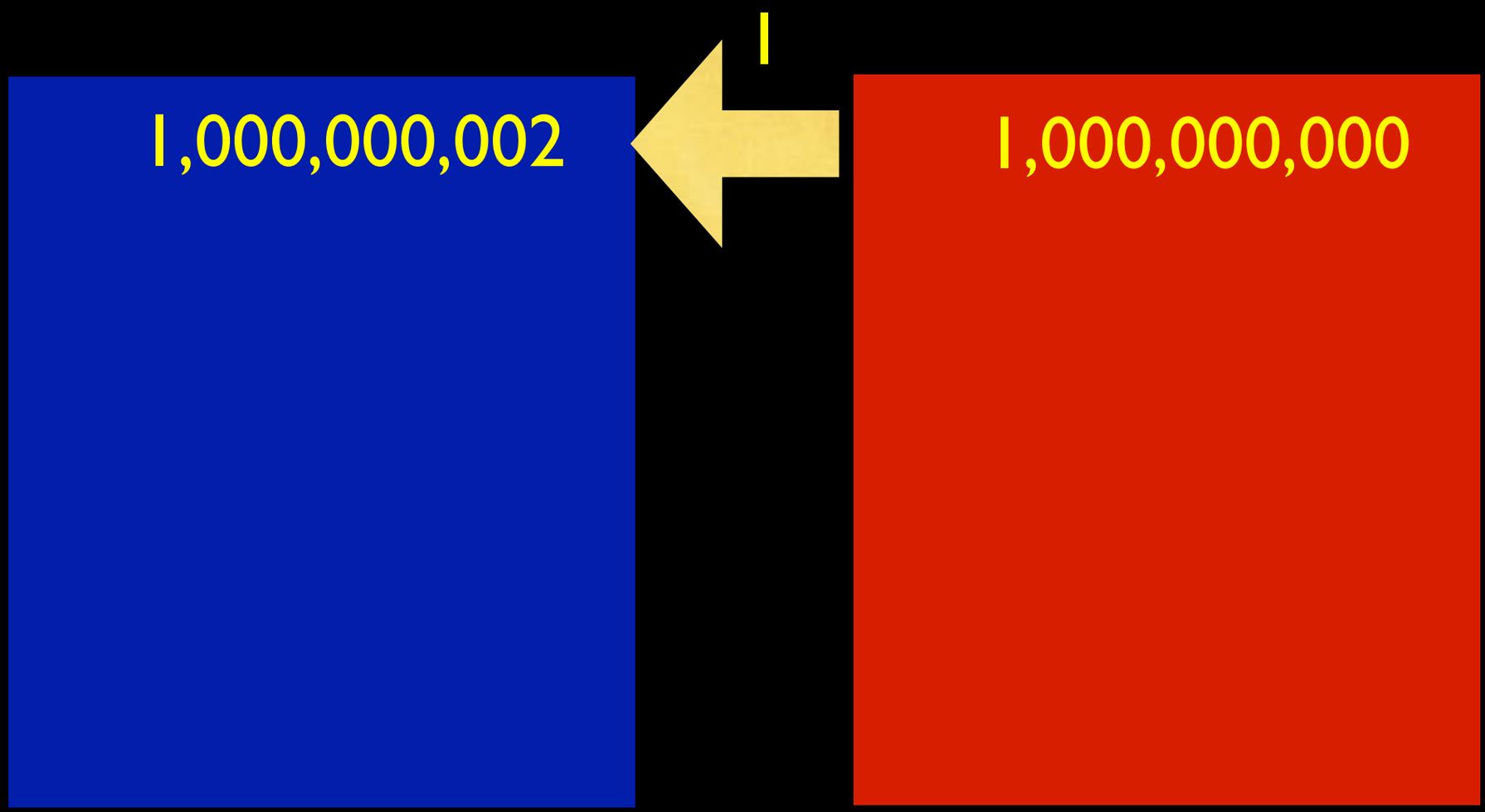
1,000,000,001

1,000,000,001

matter

anti-matter

fraction of second later



turned a billionth of anti-matter to matter

Universe Now

2

•

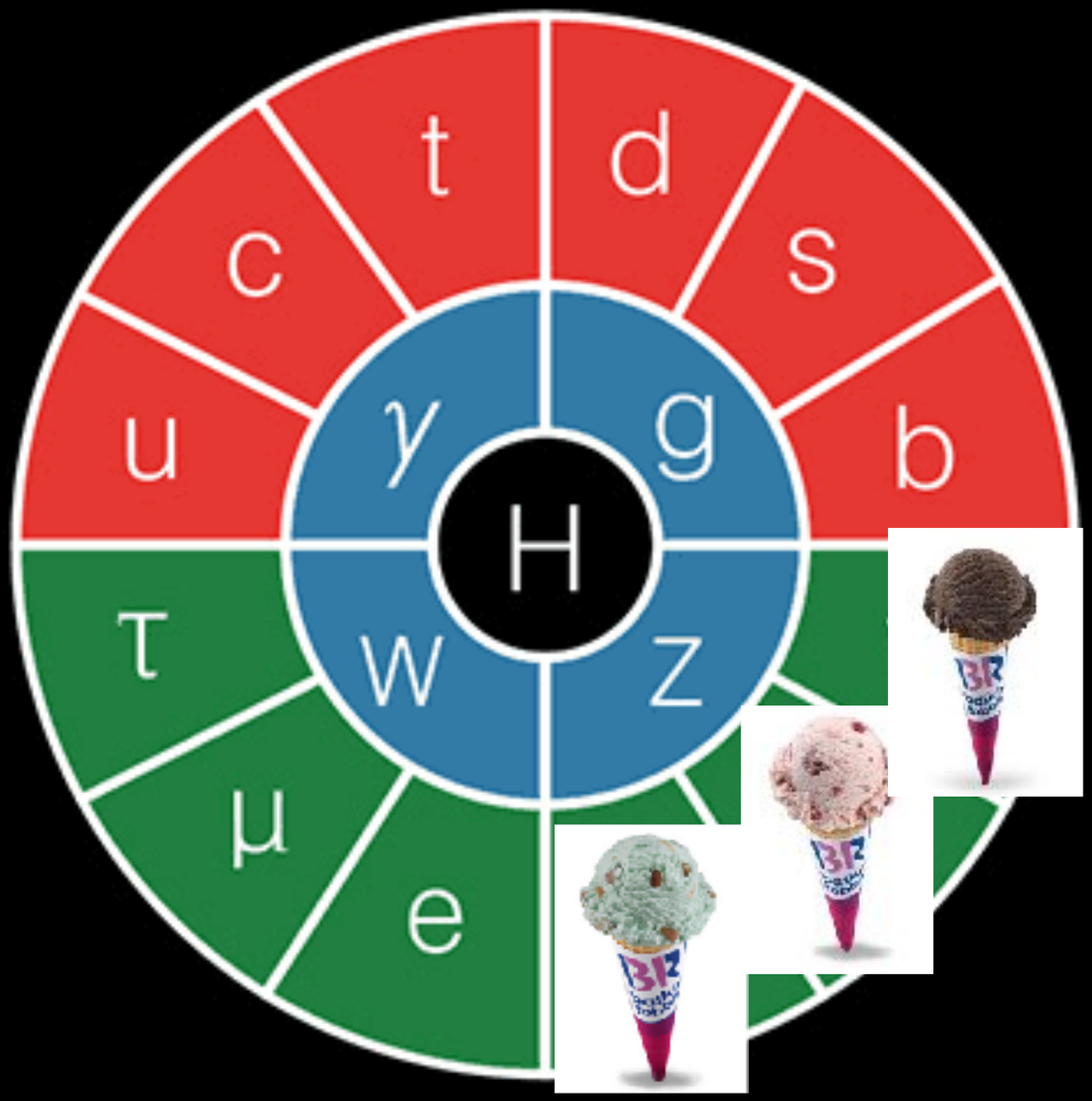
us

Can anti-matter really turn into matter?

matter *anti-matter*

This must be how we survived the Big Bang!

theory built in 100 years



FERMIONS — MATTER
- QUARKS
- LEPTONS

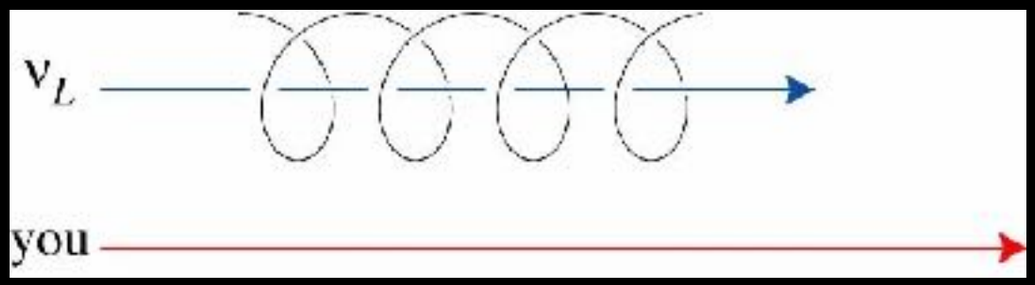
BOSONS — FORCE CARRIERS
- GAUGE BOSONS
- HIGGS BOSON

Neutrinos have no mass

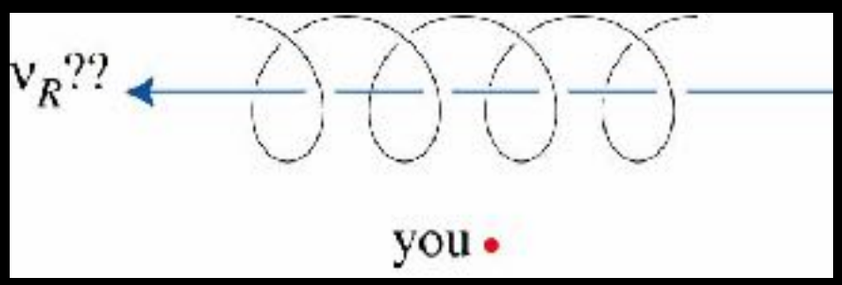
(C) Particle Fever

Neutrinos have no mass

- All neutrinos are left-handed
- If finite mass, they cannot go at speed of light

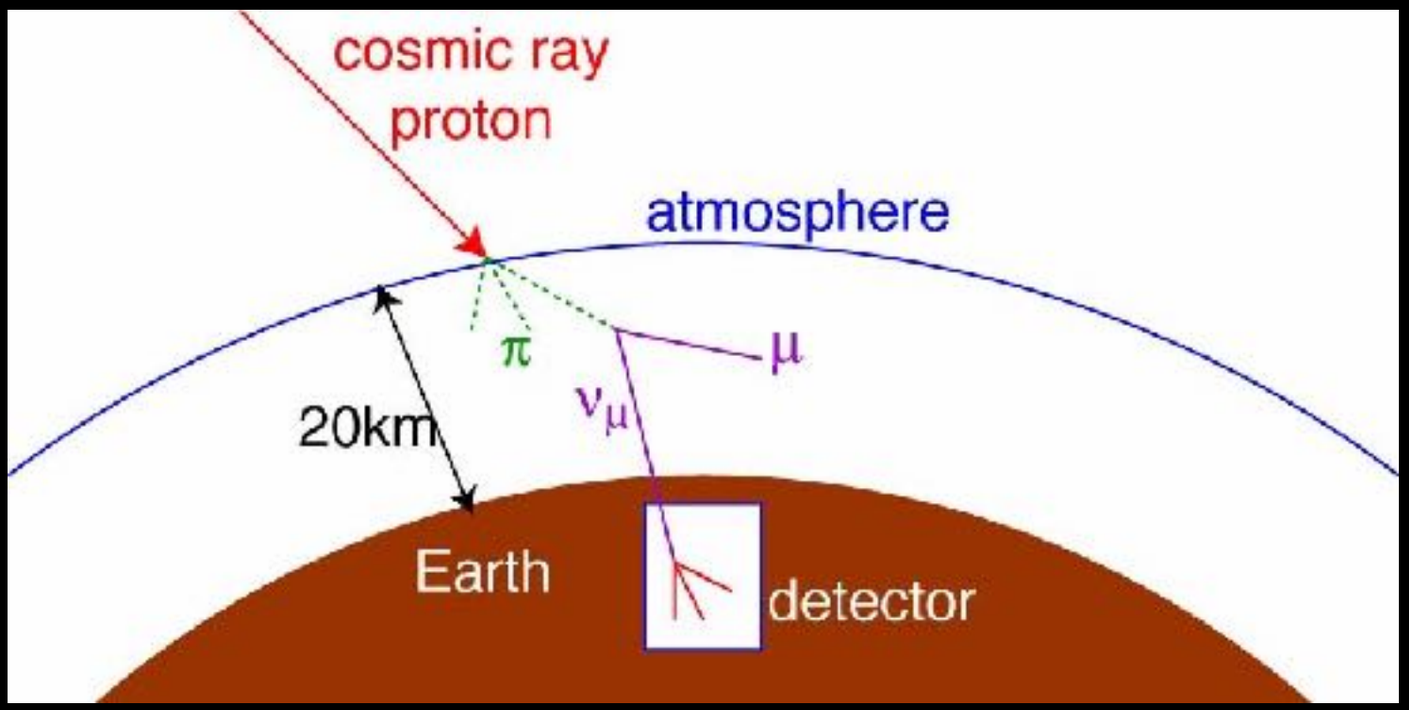


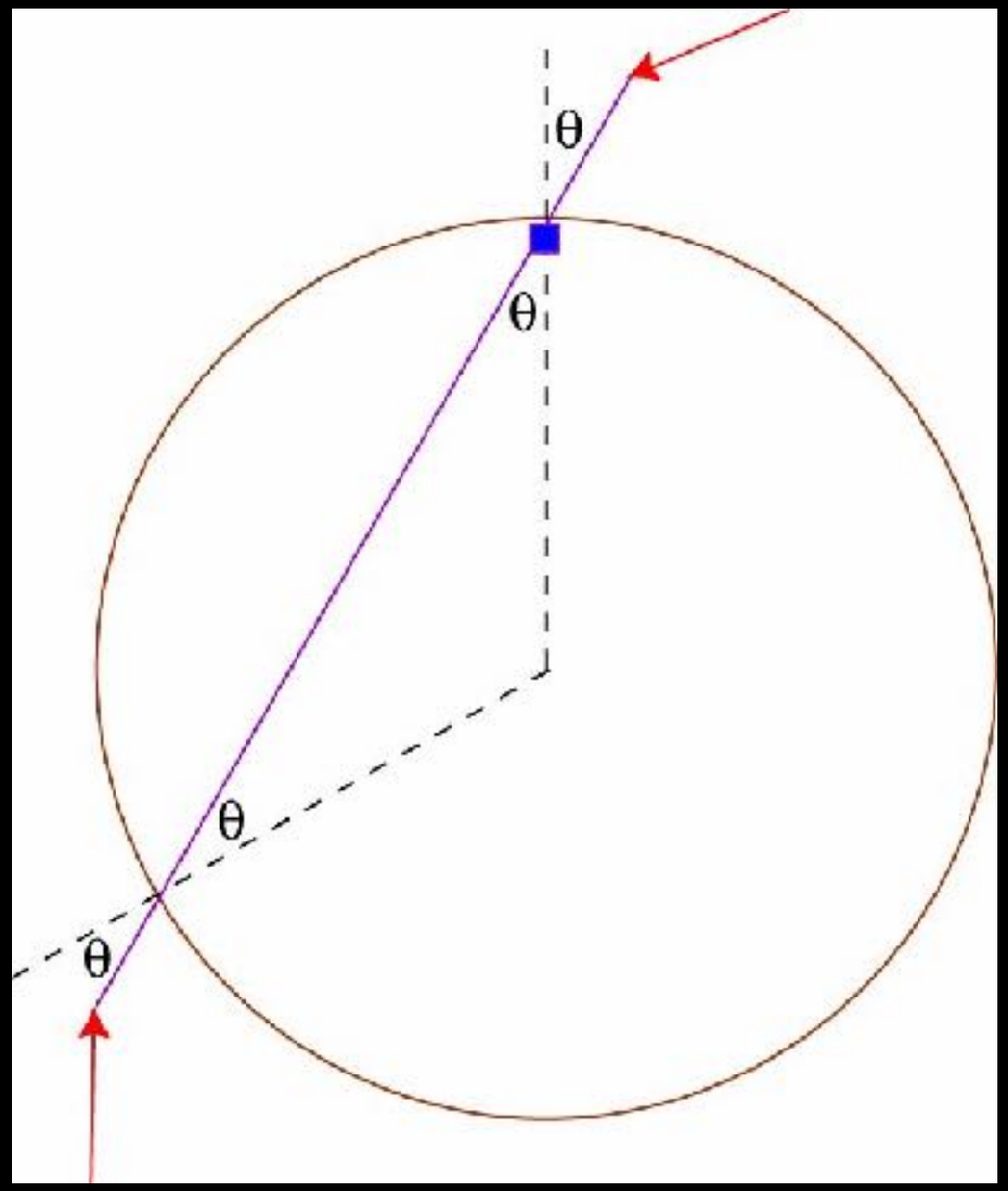
- If you look back, they appear right-handed



- Contradiction! They cannot have mass

Atmospheric neutrinos





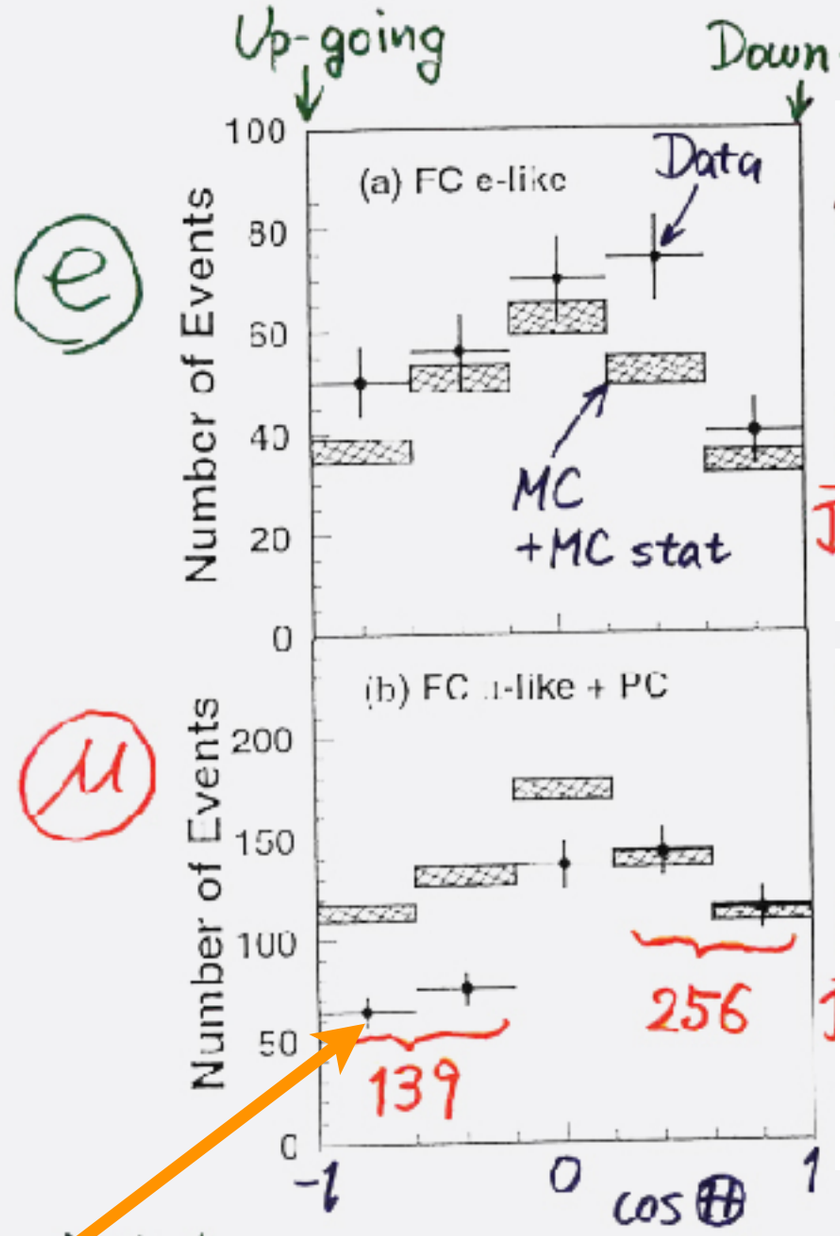
KAVLI IPMU

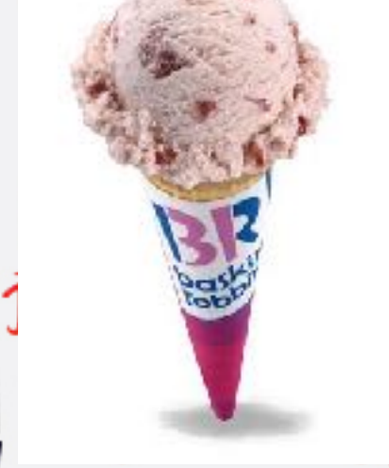
Atmospheric Neutrinos

1998

Only a half of what should be!

Zenith angle dependence (Multi-GeV)





※ Up/Down syst. error for μ-like

Prediction (flux calculation ····· ≲1%, 1km rock above SK ···· 1.5%) 1.8%

Data (Energy calib. for ↑↓ ···· 0.7%, Non ν Background ·····< 2%) 2.1%

Can taste only strawberry

Can taste only strawberry

Can taste only strawberry

Can taste only strawberry

Can taste only strawberry

Can taste only strawberry

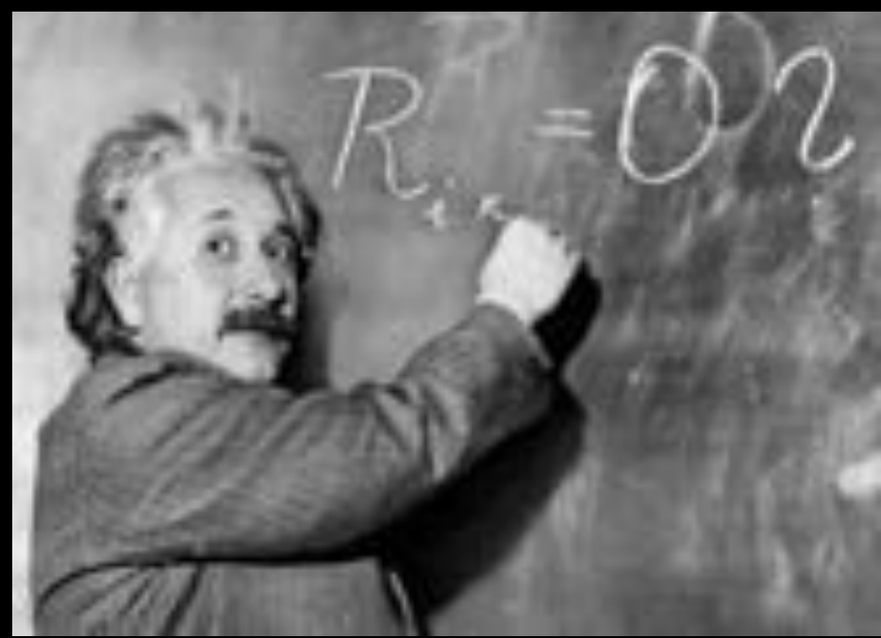
Can taste only strawberry

Can taste only strawberry

Feel you've lost a half of them!

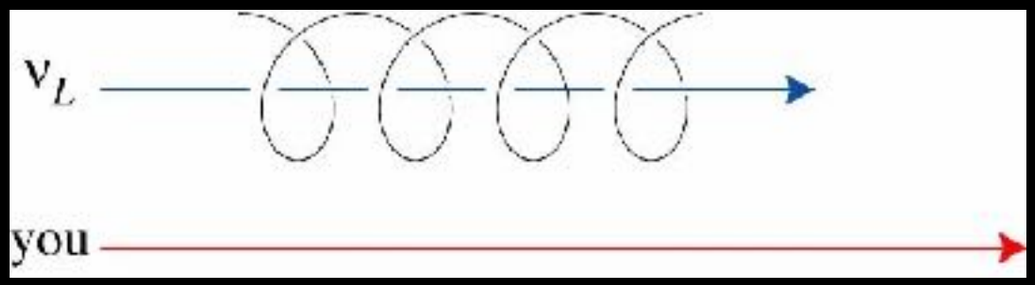
Neutrinos have mass

- Einstein's Relativity
  - Massive particles never reach speed of light
  - Massless particles (e.g. photon) always go at speed of light
- Time slows down if running fast $\Delta\tau = \Delta t\sqrt{1-\frac{v^2}{c^2}}$
  - Time stops at speed of light $\Delta\tau = 0$
- Neutrinos sense time
- Then they are slower than light
- They must have mass!

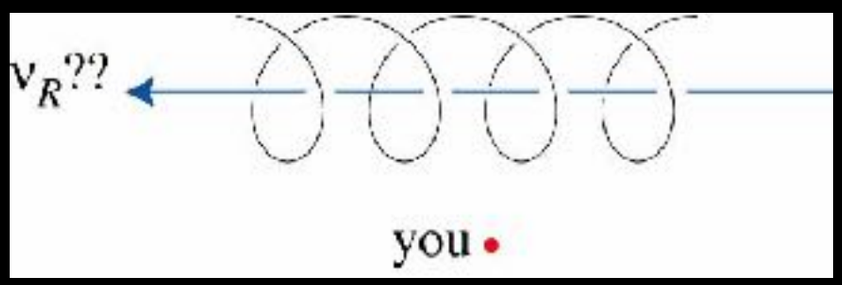


A new puzzle

- All neutrinos are left-handed
- If finite mass, they cannot go at speed of light



- If you look back, they appear right-handed



- Perhaps it is anti-neutrino?

New Paradigm

- Maybe neutrinos could reshuffle the balance between matter and anti-matter
- Possible if neutrino can morph into anti-neutrino and back
- Then we owe our existence to neutrinos!

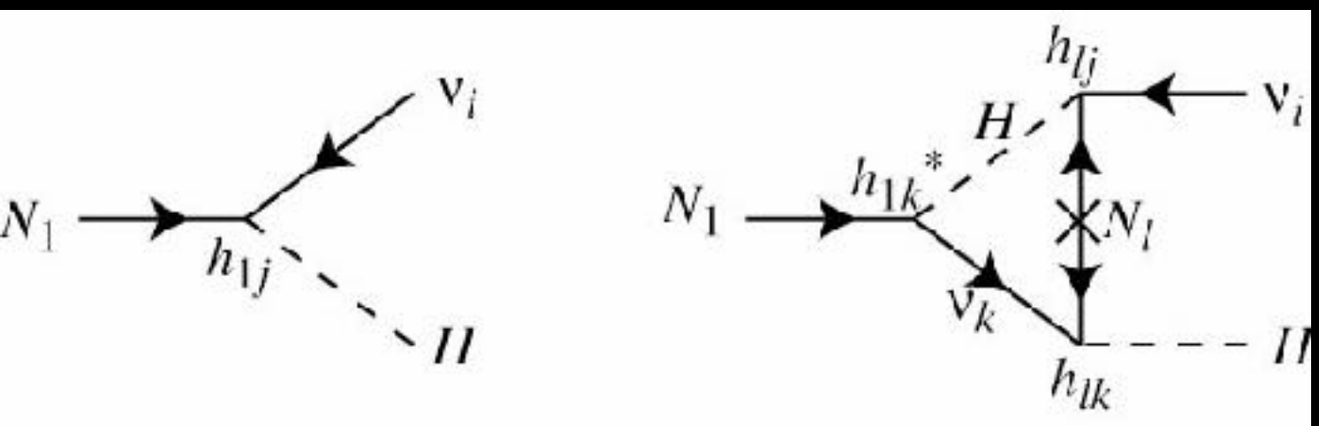

Fukugita Yanagida

Leptogenesis

- Presumably three ν_R
- One of them lives long and decays late
- Majorana: $\nu_R = \bar{\nu}_R$

- @tree-level, decays 50:50 to ν_L+h, $\bar{\nu}_L$+h*
- @one-loop,

$$\Gamma(\nu_R \to \nu_L + h) \propto 1 - \epsilon$$
$$\Gamma(\nu_R \to \bar{\nu}_L + h^*) \propto 1 + \epsilon$$

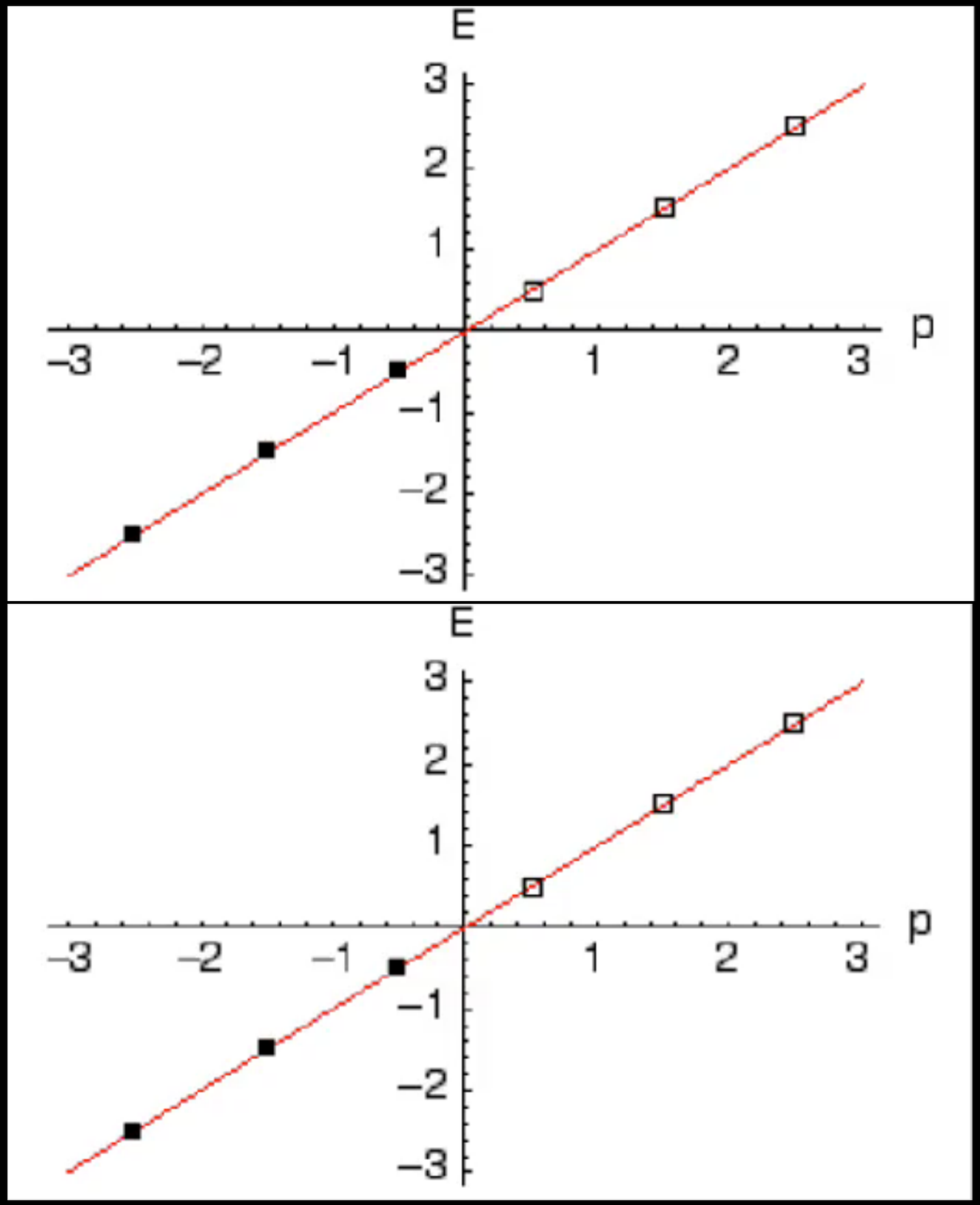


$\Delta L \neq 0$

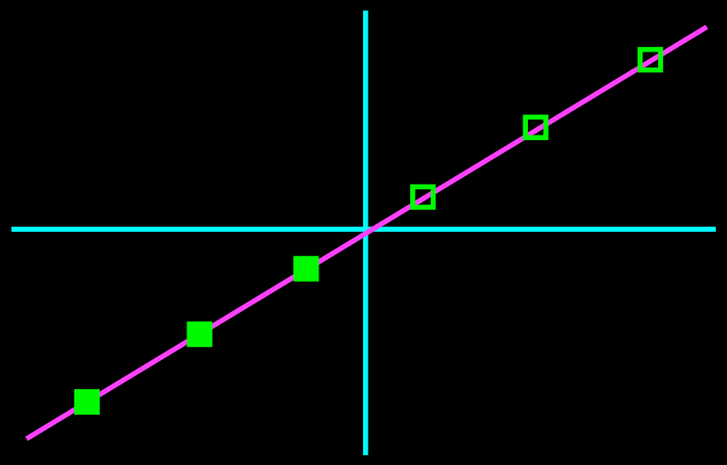
Anomaly!

- *W* and *Z* bosons massless at high temperature
- *W* field fluctuates just like in thermal plasma
- solve Dirac equation in the presence of the fluctuating *W* field

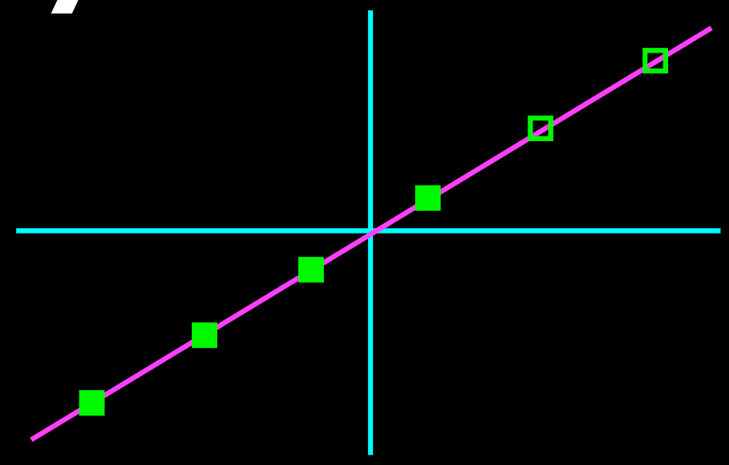
$$\Delta q = \Delta q = \Delta q = \Delta L$$



What anomaly can do



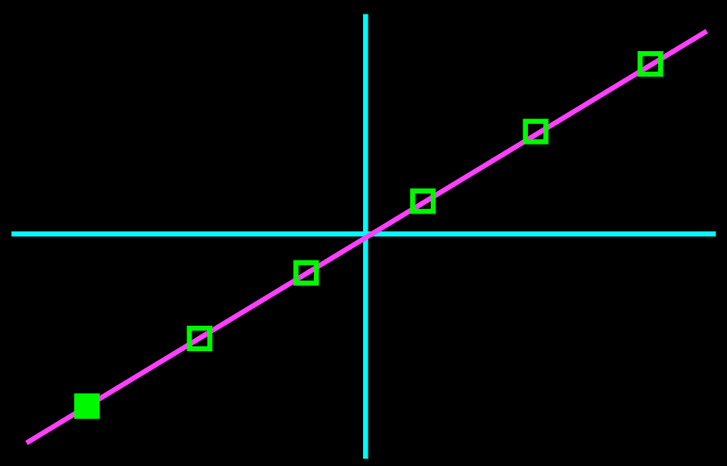
- 1,000,000,000 q



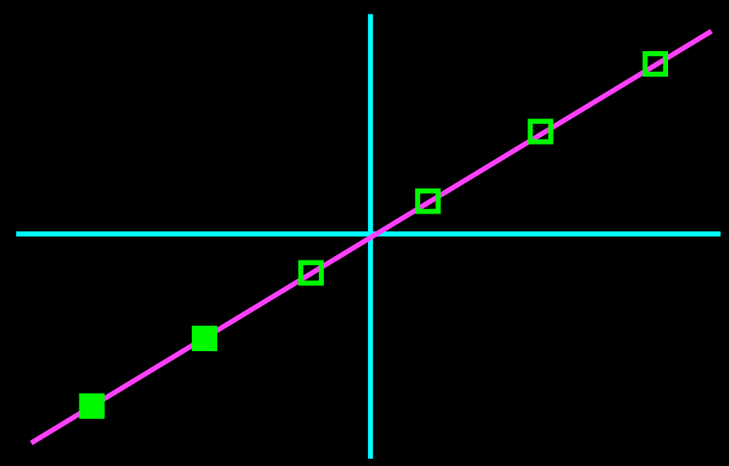
- 1,000,000,001 q

$B=0$
$L\neq 0$

- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,002 $\bar{\nu}$

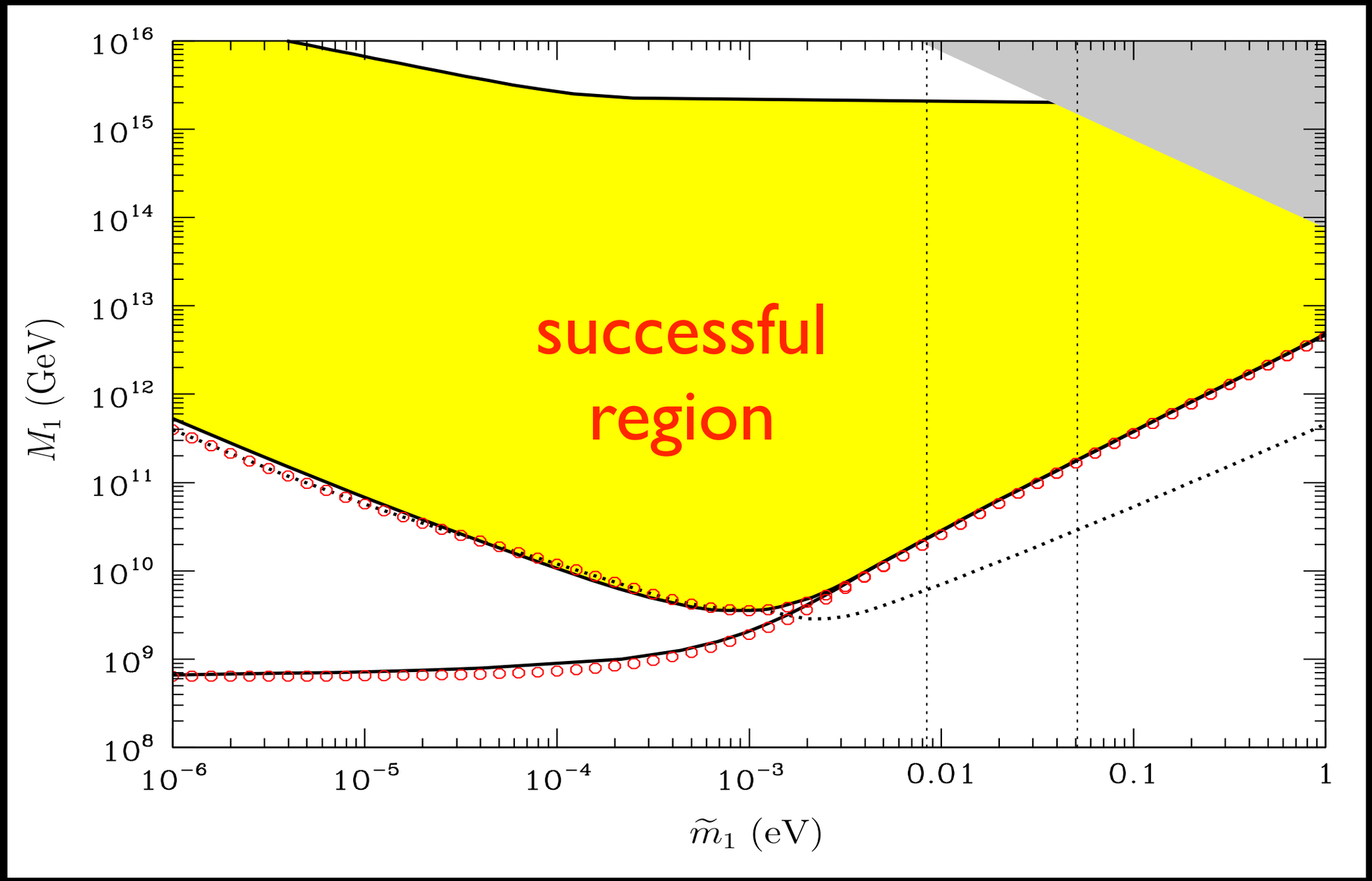


- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,001 $\bar{\nu}$



$B\neq 0$
$L\neq 0$

Non-trivial success!



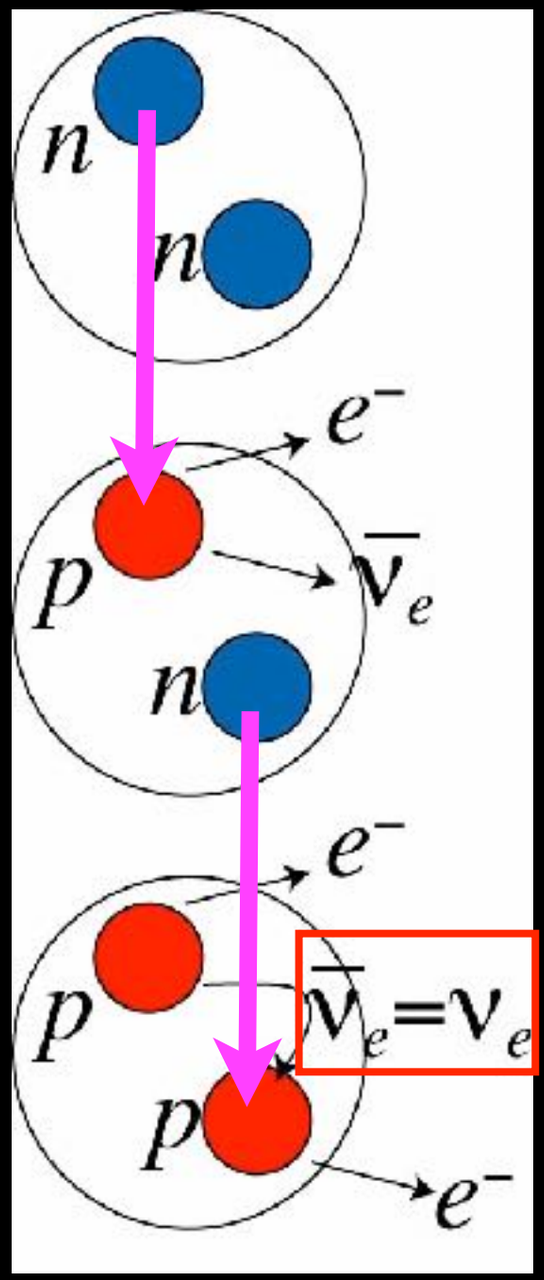
$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

di Bari, Plümacher, Buchmüller

Turn anti-matter into matter

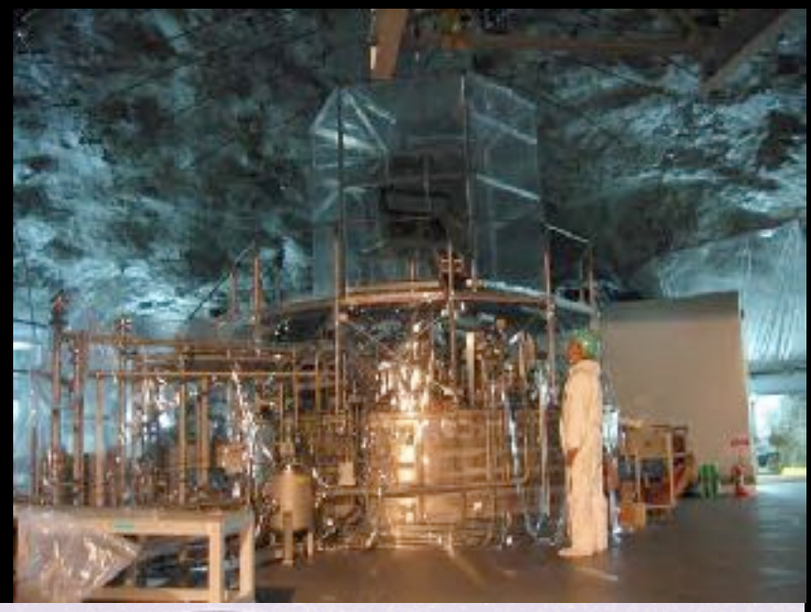
- Can anti-matter turn into matter?
- Maybe anti-neutrino can turn into neutrino because they don't carry electricity
- $0\nu\beta\beta$: $nn \rightarrow ppe^-e^-$ with no neutrinos
- doesn't happen even once 10^{26} (hundred trillion trillion) years

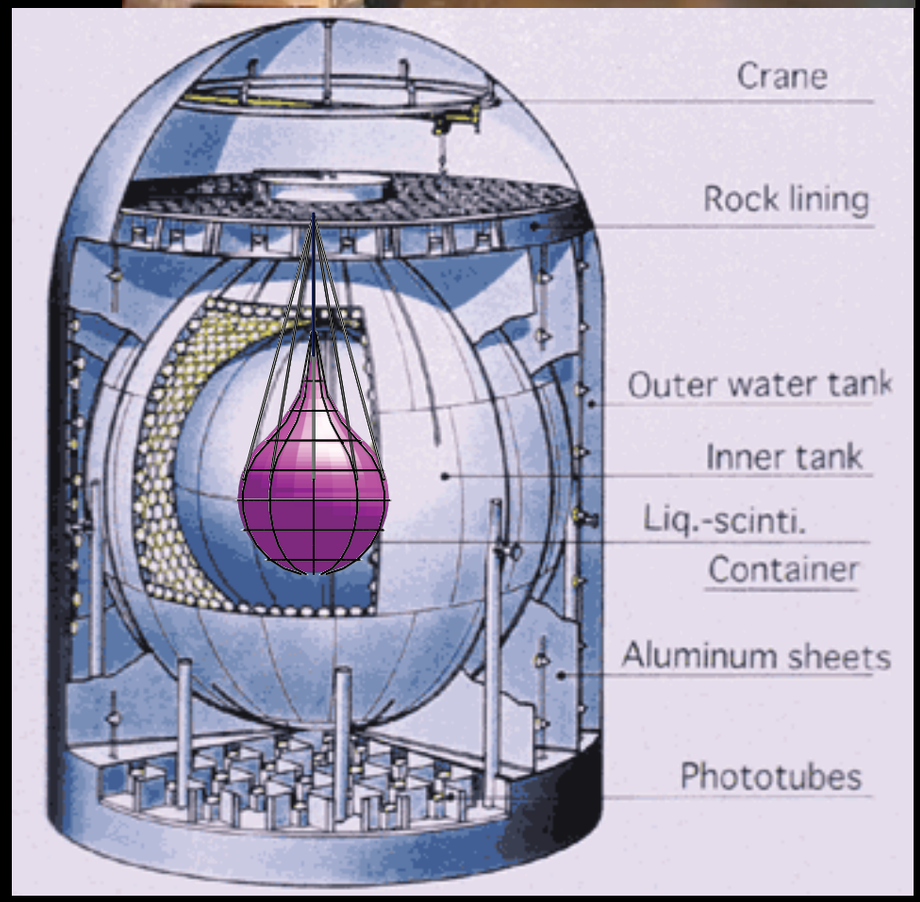
patience!



Need big underground experiments

- look for $^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}\ e^- e^-$
- dissolve gaseous xenon into liquid scintillator
- current 800kg of enriched xenon





KamLAND=1000t

History of the Universe

10-26 seconds

ten-billionth sec

3min

380k yrs

13.8Bzyrs

Accelerators
LHC
Tevatron
RHIC

high-energy cosmic rays

Inflation

BIG BANG

?

anti-matter!

DM

CMB

possible dark matter relicts

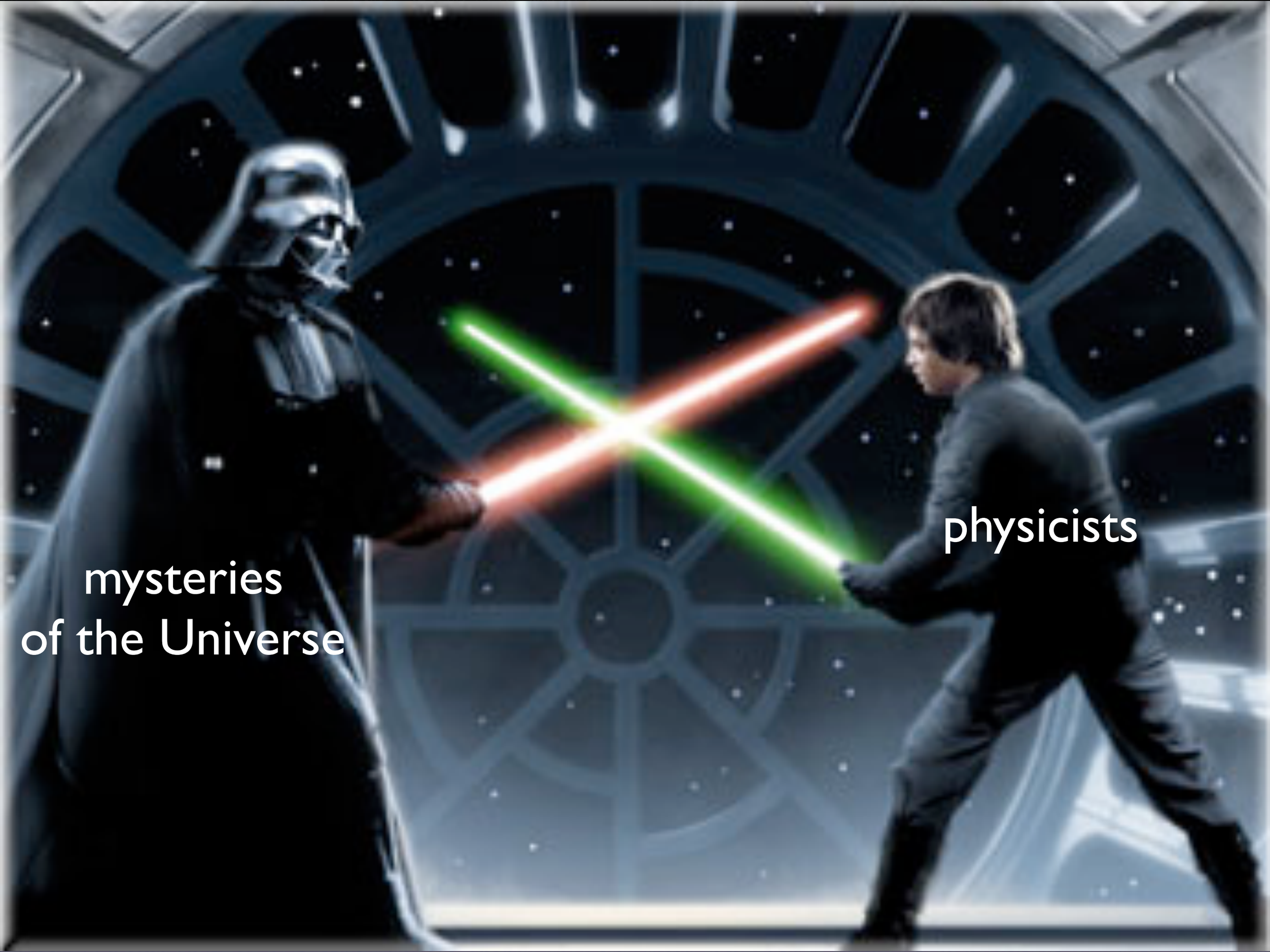
cosmic microwave radiation visible

t	10^{-44}	10^{-37} s		10^{-10} s		10^{-5} s		10^{2} s		3×10^{5} y		10^{9} y		12×10^{9} y		(sec,yrs)
T	10^{32}	10^{28}		10^{15}		10^{12}		10^{9}		3000		15		2.7		(Kelvin)
E	10^{19}	10^{15}		10^{2}		10^{-1}		10^{-4}		3×10^{-10}		10^{-12}		2.3×10^{-13}		(GeV)

Today

Key:

- W, Z bosons
- photon
- q quark
- qq meson
- galaxy
- g gluon
- qqq baryon
- star
- e electron
- μ muon τ tau
- ion
- ν neutrino
- atom
- black hole


physicists
mysteries
of the Universe


We can study the
Cosmos from
Underground!